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Terrestrial Carbon Observation

The Rio de Janeiro recommendations for terrestrial and atmospheric measurements

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Terrestrial Carbon Observation

The Rio de Janeiro recommendations for terrestrial and atmospheric measurements

February 2001

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Foreword

This report is a comprehensive plan to use *in situ* and satellite observing systems to assess and monitor carbon stocks on land an in the atmosphere.

The plan was endorsed by the major earth observing agencies and the in situ observing systems at the sixth meeting of the Integrated Global Observing System Partners. It lays out the way forward for countries to systematically measure and monitor the amounts of carbon in their forests, crops, rangelands, soil and atmosphere.

Why is carbon important? One could make many arguments in favour of its relevance to science, policy and sustainable development. However, in the view of FAO, foremost among these is the important role that carbon plays in sustaining agricultural productivity, biodiversity, and forest ecosystem processes. It is one of the essential ingredients to producing sufficient food, fodder, and forest products that are so important to the economies of lower income countries.

As such, there is the close link between this work and the issues that were recently taken up at the World Food Summit: five years later. Many of our member countries suffer not only from lack of access to food and chronic drought but also from vulnerability to longer-term changes that may affect their ability to produce food.

FAO has a long history of developing methodologies and technical tools aimed at sustainable agriculture and rural development and the Global Terrestrial Observing System (GTOS), which FAO has been hosting for the past seven years, is a key programme for doing this in collaboration with a number of key partners, including the International Geosphere-Biosphere Programme, a variety of research institutes, satellite agencies and several United Nations organizations.

The Terrestrial Carbon Observation (TCO) initiative is a logical extension of our previous work and takes us into new and emerging areas of science and policy. Effective management of the carbon cycle will contribute not only to sustainable increases in rural productivity but also to a national understanding of the role of each country in the ongoing discussions related to climate change. Better data and information about conditions and trends in countries will strengthen their position at regional and international fora.

This report provides the basis for making the systematic, long-term observation in terrestrial systems and in the atmosphere that are needed to address issues related to rapid environmental changes, including the loss of biological diversity, desertification and climate change.

We look forward to continued collaboration and progress in developing the TCO initiative.

Jacques Eckebil
Assistant Director-General
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This One
TRZQ-PCS-WUEC

Terrestrial Carbon Observation: The Rio de Janeiro recommendations for terrestrial and atmospheric measurements.

Editors J. Cihlar, S. Denning

* Refer to Appendix 4 for affiliations

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ABSTRACT

February 2001

The Integrated Global Observing Strategy Partnership (IGOS-P) is using specific policy-relevant themes as an approach to implementing systematic global observations. In November 1999, IGOS-P requested Global Terrestrial Observing System with FAO support, to lead the Terrestrial Carbon Cycle theme. In response to the request, the Terrestrial Carbon Theme Team was established to prepare this report. The report identifies a set of systematic, long-term terrestrial and atmospheric observations needed to implement an effective terrestrial carbon observation programme, highlights a number of challenges that need to be addressed, and outlines an approach to implementing an initial observing system. "Terrestrial carbon" refers to carbon contained in terrestrial vegetation or soil stocks and the fluxes from or to the atmosphere through which it participates in the global carbon cycle.

This series replaces the following:
- Environment and Energy Series
- Remote Sensing Centre Series
- Agrometeorology Working Paper

A list of documents published in the above series and other information can be found at the following Web site: www.fao.org/sd

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Jeff Tschirley
GTOS Programme Director

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ABBREVIATIONS

AATSR	Advanced Along-Track Scanning Radiometer
ADEOS	Advanced Earth Observation Satellite
AIRS	Atmospheric Infrared Sounder
ALI	Advanced Land Imager
ALOS	Advanced Land Observing Satellite
AMI	Active Microwave Instrument
AMSR	Advanced Microwave Scanning Radiometer
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced Scatterometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATSR	Along Track Scanning Radiometer
AWiFS	Advanced Wide Field Sensor
AVHRR	Advanced Very High Resolution Radiometer
AVNIR	Advanced Visible and Near-Infrared Radiometer
BAHC	Biospheric Aspects of the Hydrological Cycle
CAST	Chinese Academy of Space Technology
CCRS	Canada Centre for Remote Sensing
CESBIO	Centre d'Etudes Spatiales de la Biosphère
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and Earth's Radiant Energy System
CH_4	Methane
CMIS	Conical Scanning Microwave Imager/Sounder
CNES	Centre National d'Etudes Spatiales
CO	Carbon monoxide
CO_2	Carbon dioxide
COBRA	CO_2 Budget and Rectification Airborne
COP	Conference Of Parties
CSA	Canadian Space Agency
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DISS	Data and Information Systems and Services
DOD	Department of Defence (USA)
ENVISAT	ESA Satellite
EO	Earth Observing
EOS – Aqua	Earth Observation Satellite - Water
EOS – Aura	Earth Observation Satellite - Air
EOS – Terra	Earth Observation Satellite - Land
EPIC	Earth Polychromatic Imaging Camera
ERBE	Earth Radiation Budget Experiment
ERS	European Remote Sensing satellite
ESA	European Space Agency
ESRIN	European Space Research Institute
ESSP	Earth System Science Pathfinder
ETM	Enhanced Thematic Mapper
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FAO	Food and Agriculture Organization of the United Nations
FDGC	Federal Geographic Data Committee (USA)
FLUXNET	Flux Network
FRA	Forest Resources Assessment
GAIM	Global Analysis, Intergrating and Modelling
GAW	Global Atmospheric Watch
GCMD	Global Change Master Directory
GCOM	Global Change Observation Mission
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems
GEWEX	Global Energy and Water Cycle Experiment
GLAS	Geoscience Laser Altimeter System (formerly GLRS-A)
GLI	Global Land Imager
GOES	Geostationary Operational Environmental Satellite
GOFC	Global Observation of Forest Cover
GOOS	Global Ocean Observing System
GOSIC	Global Observing Systems Information Center
GOSSP	Global Observing Systems Space Panel

GT-Net	Global Terrestrial Observing Network
GTOS	Global Terrestrial Observing System
GUAN	GCOS Upper Air Network
HIRDLS	High-Resolution Dynamics Limb Sounder
HPREN	High Performance Research and Education Networks
HRG	High Resolution Geometry
HR-PAN	High Resolution Panchromatic sensor
HRV	High Resolution Visible
IASI	Improved Atmospheric Sounding Interferometer
ICESat	Ice, Cloud, and Land Elevation Satellite
ICSU	International Council for Science
IGAC	International Global Atmospheric Chemistry
IGBP	International Geosphere-Biosphere Programme
IGCO	Integrated Global Carbon Observations
IGOS	Integrated Global Observing Strategy
IGOS-P	Integrated Global Observing Strategy Partnership
IJPS	Initial Joint Polar-Orbiting Operational Satellite System
ILAS	Improved Limb Atmospheric Spectrometer
ILTER	International Long Term Ecological Research
INPE	Instituto Nacional de Pesquisas Espaciais
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing Satellite
ISLSCP	International Satellite Land Surface Climatology Project
ISRIC	International Soil Reference and Information Centre
ISRO	Indian Space Research Organisation
IT	Implementation Team
IUSS	International Union of Soil Sciences
JERS	Japanese Earth Resources Satellite
JME	Ministry of Environment (Japan)
JRC	Joint Research Centre
LAI	Leaf Area Index
LANDSAT	Land Remote Sensing Satellite
LBA	Large Scale Biosphere-Atmosphere Experiment in Amazonia
LDAS	Land Data Assimilation System
LISS	Linear Imaging Self-Scanning sensor
LUCC	Land Use and Cover Change
MBLA	Multi-Beam Laser Altimeter
MECB	Missão Espacial Completa Brasileira
MERIS	Medium Resolution Imaging Spectrometer
MetOp	Meteorological Operational satellites
MIRAS	Microwave Imaging Radiometer with Aperture Synthesis
MISR	Multi-angle Imaging Spectro-Radiometer
MITI	Ministry of International Trade and Industry (Japan)
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
MOS	Marine Observation Satellite
MSG	Meteosat Second Generation
MSMR	Multifrequency Scanning Microwave Radiometer
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Space Development Agency (Japan)
NDVI	Normalized Difference Vegetation Index
NEP	Net Ecosystem Productivity
NERC	Natural Environment Research Council
NGO	Non-governmental Organization
NMP	New Millennium Program
NOAA	National Oceanic and Atmospheric Administration (USA)
NPOESS	National Polar Orbiting Environmental Satellite System
NPP	Net Primary Productivity
NREN	NASA Research and Educational Network
NWP	Numerical Weather prediction
ODUS	Ozone Dynamics Ultraviolet Spectrometer

ORNL	Oak Ridge National Laboratory (USA)
OSC	Orbital Sciences Corp
OSTC	Federal Office for Scientific Technical and Cultural Affairs (Belgium)
PALSAR	Phased-Array type L-Band Synthetic Aperture Radar
PAN	Panchromatic
PAR	Photosynthetically Active Radiation
PIK	Potsdam Institute for Climate Impact Research
POLDER	Polarisation and Directionality of Earth Reflectances
PR	Precipitation Radar
PRISM	Panchromatic Remote Sensing Instrument for Stereo Mapping
QuikScat	Quick Scatterometer
RADARSAT	Canadian Synthetic Aperture Radar Satellite
SAI	Space Applications Institute
SAR	Synthetic Aperture Radar
SBSTA	Subsidiary Body for Scientific and Technological Advice
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEI	Special Events Imager
SEVIRI	Spinning Enhanced Visible and Infra Red Imager
SGLI	Second Generation Globai Imager
SIT	Strategic Implementation Team (CEOS)
SMOS	Soil Moisture and Ocean Salinity
SNSB	Swedish National Space Board
SOFIS	Solar Occultation FTS for Inclined-orbit Satellite
SOMNET	Soil Organic Matter Network
SOTER	Soil and Terrain Database
SPOT	Système Pour l'Observation de la Terre
SRB	Surface Radiation Budget
SSR	Satélites de Sensoriamento Remoto
SW	Shortwave
TCO	Terrestrial Carbon Observation
TES	Tropospheric Emission Spectrometer
TIROS	Television and InfraRed Observation Satellite
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission (USA, Japan)
UNEP	United Nations Environmental Programmeme
UNFCCC	United Nations Framework Convention on Climate Change
USGCRP	United States Global Change Research Programme
USGS	United States Geological Survey
VCL	Vegetation Canopy Lidar mission
VIIRS	Visible/Infrared Imager/Radiometer Suite
VIRS	Visible Infrared Scanner
WCMC	World Conservation Monitoring Centre
WCRP	World Climate Research Programme
WFW	World Fire Web
WGCV	Working Group on Calibration and Validation (CEOS)
WGISS	Working Group on Information Systems and Services (CEOS)
WiFS	Wide Field Sensor
WMO	World Meteorological Organization
WRI	World Resources Institute

Executive Summary

THE INTEGRATED GLOBAL OBSERVING STRATEGY PARTNERSHIP (IGOS-P) IS USING SPECIFIC POLICY-RELEVANT THEMES AS AN APPROACH TO IMPLEMENTING SYSTEMATIC GLOBAL OBSERVATIONS. IN NOVEMBER 1999, IGOS-P REQUESTED GTOS, WITH FAO SUPPORT, TO LEAD THE TERRESTRIAL CARBON CYCLE THEME AND FORM A THEME TEAM. This report identifies a set of systematic, long-term terrestrial and atmospheric observations needed to implement an effective terrestrial carbon observation programme, highlights a number of challenges that need to be addressed, and outlines an approach to implementing an initial observing system. 'Terrestrial carbon' refers to carbon contained in terrestrial vegetation or soil stocks and the fluxes from or to the atmosphere and oceans through which it participates in the global carbon cycle. The 1999 IGOS-P meeting also endorsed the preparation of an overarching global carbon cycle theme which has since been initiated through the Integrated Global Carbon Observation (IGCO) theme and which provides the framework for integrating the terrestrial, atmospheric and oceanic components. In the IGCO context, this report deals with the terrestrial and atmospheric components of the global carbon cycle.

Information on the terrestrial carbon distribution and changes is required by several policy and research areas. Key among these are (i) national commitments to environmental conventions and multilateral agreements that require terrestrial carbon information; (ii) acceptance by the Conference of Parties of the need for systematic observations and reporting within the UN Framework Convention for Climate Change, including the Kyoto Protocol; (iii) the need for information on the productivity and changes of terrestrial biosphere which, together with land use and other information form a basis for sustainable development and resource management, and (iv) improved knowledge of the carbon cycle, to allow more effective policy development to deal with climate variability, change, impact and adaptation. Accordingly, users of terrestrial carbon information range from national ministries (for policy setting, reporting, sustainable development planning) to international scientific and policy bodies.

Although various important building blocks for systematic global carbon observation already exist, there are gaps and deficiencies as well as a lack of coordination and continuity. Therefore, a focused and dedicated effort is needed to implement an initial observing system. The following goals are proposed for the initial system, with a timetable partly conditioned by the schedule of the Kyoto Protocol:

1. By 2005, demonstrate the capability to estimate annual net land-atmosphere fluxes at a subcontinental scale (10^7 km^2) with an accuracy of +/- 30% globally, and a regional scale (10^6 km^2) over areas selected for specific campaigns with a similar or better accuracy;
2. By 2008, improve the performance to better spatial resolution (10^6 km^2 globally) and an increased accuracy (+/- 20%);
3. In each case, produce flux emission estimate maps with the highest spatial resolution enabled by the available satellite-derived and other input products.

To achieve these goals, IGOS-P needs to ensure the acquisition of surface and satellite observations for a range of products, the preparation of these products, and their use in models of carbon exchange with the atmosphere to yield estimates of sources and sinks of terrestrial carbon on an annual basis. An important associated objective is a research and development programme that will lead to continuing improvements in the comprehensiveness and quality of the observation methods, products and model outputs.

The economic and social significance of many aspects of the carbon cycle have led to numerous terrestrial and atmospheric observation initiatives undertaken or planned. Thus the primary roles for IGOS-P in establishing a long-term terrestrial carbon observation programme are to ensure that gaps in the observing systems are filled; to achieve continuity, consistency and ongoing improvements in the observing capabilities; and to facilitate coordination and collaboration among the contributors so that the products have the expected utility and impact. Regarding observation capabilities, this report identifies issues that need to be addressed in two major challenges, long term continuity and consistency of observations (25 issues) and knowledge development (28 issues).

Regarding the **long-term continuity and consistency** challenge, the major issues may be summarized as follows:

I SATELLITE OBSERVATIONS

a Land cover and change, seasonal growth cycle, fires:

1. Continuity of calibrated, fine resolution satellite optical measurements from both fixed-view and pointable sensors, as well as Synthetic Aperture Radar (SAR) data. This data should be accompanied by a consensus strategy for global satellite data acquisition at fine resolution.

b Biomass:

2. Ongoing availability of, and improvements in, canopy structure measurements from satellite sensors, beyond the planned Vegetation Canopy Lidar Earth System Science Pathfinder mission.

c Product generation:

3. Institutional arrangements for product generation and quality control, including incorporation of *in situ* observations as appropriate, intercalibration between missions, and reprocessing of archived data.

II *IN SITU* OBSERVATIONS

a Ecological and soil observations:

4. Increased density of *in situ* observations and more

effective access to and use of data available within countries, in combination with satellite-derived products.

b Surface-atmosphere fluxes:

5. Maintaining the existing flux measurement programmes for at least ten years at a site. Expanding the current network in underrepresented geographic regions and ecosystem conditions, and improving international coordination of data handling and use. In addition, continuously operate selected long-term stations to serve as anchor sites for understanding climate variability.
6. Ensuring that the expanded *in situ* networks provide data to improve the quality of satellite-derived products and the performance of biogeochemical models.

c Atmospheric concentration measurements:

7. Ensuring the long-term continuity and stability of the global air flask sampling programmes, including support for improved accuracy and inter-laboratory calibration.
8. Adding sites to the existing air flask sampling network to improve results of atmospheric inversions for the terrestrial ecosystems.
9. Ensuring increases in the resolution and coverage of fossil fuel emission data provided by national agencies.

The 28 **knowledge development** issues concern the new observing, analysis and modeling tools that are essential to improve the quality or comprehensiveness of the acquired terrestrial carbon information. Progress in these areas should be regarded as an integral and necessary part of the systematic, long-term observation scheme.

It is recommended that IGOS Partners:

1. Request that the IGCO Theme Team use this report in preparing the IGCO theme report.
2. request the Strategic Implementation Team (SIT) to review and confirm the commitments to existing and planned missions and programmes (Appendix 3.).
3. examine the specific continuity and knowledge challenge issues identified in this report and where feasible, allocate responsibility for addressing the gaps.
4. take the following initial steps toward TCO implementation, within the IGCO framework:
   a) identify lead IGOS Partner(s) responsible for TCO implementation;
   b) charge the lead Partner to prepare draft terms of reference in consultation with the Partners and to establish a TCO Implementation Team as outlined in section 6.2;
   c) request TCO Implementation Team (IT) to submit a draft work plan with required IGOS-P contributions (beyond those in recommendations 2 and 3 above) within 4 months of the IT establishment;
   d) agree to support the work of TCO IT by making available staff and financial resources for its activities; and commit to responding to the TCO IT work plan within three months following its delivery.

1

Introduction and background

AN ACCURATE KNOWLEDGE OF THE GLOBAL CARBON CYCLE HAS BECOME POLICY IMPERATIVE FOR THIS AND THE FORTHCOMING DECADES, BOTH GLOBALLY AND FOR INDIVIDUAL COUNTRIES. INCREASING ATMOSPHERIC CO_2 CONCENTRATION DUE TO HUMAN ACTIVITY IS AN IMPORTANT CAUSATIVE FACTOR FOR POTENTIAL CLIMATE VARIABILITY AND CHANGE. This recognition has placed the global carbon cycle at the forefront of policy debates and scientific studies. The priority being given to an improved understanding of the carbon cycle is very likely to continue into the foreseeable future. For example, the Kyoto Protocol recognizes the role of terrestrial systems as carbon sinks and sources, and it provides a basis for developing future emission trading arrangements that involve forests and potentially other ecosystems. Understanding of the pathways through which the anthropogenic CO_2 leaves the atmosphere and enters into ecosystems, thus offsetting a portion of the human-caused emissions is incomplete, at best. For example, about 15-30% of the anthropogenic carbon emissions cannot presently be accounted for (decadal average; annual uncertainties are higher), and are presumed to be absorbed by terrestrial ecosystems. A more accurate knowledge of the sequestration of the carbon emissions is therefore critical to implementing effective carbon–related policies. Of equal importance is the ability to predict the evolution of the atmospheric CO_2 concentration in order to optimise mitigation strategies.

In addition to the environmental policy dimension, the distribution and quantification of terrestrial carbon (i.e. carbon in the vegetation or soils) has important economic and resource management implications. For example, the yield of agricultural, forest, and rangeland resources is directly related to the amount of carbon tied up in the aboveground biomass. Thus, improved information on the distribution and changes in carbon content and better understanding of the terrestrial carbon cycle will contribute to more effective use and management of agricultural, forest, and rangeland resources.

The global carbon cycle connects the three major components of the earth system: the atmosphere, oceans, and land. In each domain, large pools of readily exchangeable carbon are stored in various compartments ('pools' or 'stocks'). Large amounts of carbon ('fluxes') are transferred between the pools over various time periods (daily, annual, decadal, etc.). Although some of the fluxes are very large, the net change over a given time period need not be. For many centuries prior to the industrial revolution the carbon pools were more or less in equilibrium, and the net transfer was close to zero over sufficiently large areas or, in case of smaller areas, over sufficiently long periods of time. The major change occurred following industrialization, with the accelerated transfer from the geological pool (fossil fuels) to the atmosphere. Because of the connections among pools, the increased atmospheric carbon concentration affects the other connected pools in oceans and on land. The processes governing the fluxes between the pools take place at various speeds, from daily to centennial and longer. These factors and dependencies make the quantification and study of the carbon cycle very challenging, and they need to be taken into consideration when designing a strategy for a carbon observing system.

The environmental, economic and societal importance of the perturbation of the carbon cycle led to numerous activities at national and international levels. It has become widely appreciated that appropriate responses to this issue require better understanding of the current and future evolution of the atmospheric, land and ocean pools, supported by accurate observations of the magnitudes and trends of the fluxes. Recognizing these factors, IGOS-P responded to a proposal to consider the establishment of systematic terrestrial carbon observation which was submitted to the November 1999 meeting by GTOS. IGOS-P decisions were:

- Action 4/5 GTOS with FAO support to lead the Terrestrial Carbon Cycle theme and to present a report to the Partners along the lines of the Oceans theme report.
- Action 4/6 GCOS, FAO, IGBP, ICSU, UNESCO, and CEOS to nominate representatives for the Terrestrial Carbon Cycle team by the end of November 1999.
- Action 4/9 GOOS, GCOS, GTOS, IGBP, NASA to prepare proposals for the overarching Global Carbon Theme and to decide amongst themselves who should lead this activity.

In response to Action 4/5 and 4/6, a Terrestrial Carbon Theme Team representing various IGOS Partners has been established and produced this report. The report describes the terrestrial and the associated atmospheric components of the global carbon cycle. It incorporates inputs from several science workshops focused on this topic: GTOS-IGBP Terrestrial Carbon Observation Synthesis Workshop in Ottawa, Canada (8-11 February; Cihlar, Denning and Gosz 2000); the EU-IGBP-GTOS Terrestrial Carbon Meeting in Costa da Caparica, Portugal (22-26 May 2000) and the EU-IGBP-IHDP-WCRP international workshop on carbon cycle research in Durham, New Hampshire (16-20 October 2000), in addition to the Team members' contributions. Other GTOS and GCOS documents were also used in preparing this report. In parallel, a report on ocean carbon observation is being prepared for IGOS-P.

Action 4/9 led to the proposal for an Integrated Global Carbon Observation (IGCO) theme (Steffen, 2000). IGCO is designed as an overarching theme which will integrate terrestrial, atmospheric and ocean components of the global C cycle as well as ensure linkages to socioeconomic and other relevant issues. The integration of the terrestrial and oceanic reports will be subject of future efforts as part of IGOS-P planning.

Consistently with IGOS-P aims, this report focuses on systematic, long-term global observation requirements and thus does not present all the observations needed about the carbon cycle; the above source reports present a more complete picture in this respect. In addition, the report focuses on CO_2 as the most important gas from the perspective of climate change, with the major exception of methane (p.20). In the future, it may be possible to address other gases relevant to the carbon cycle in a more systematic manner.

The main sections of the report are: motivation for systematic terrestrial carbon observation (Chapter 2); existing observing activities and capabilities (Chapter 3); major, urgent continuity and consistency issues requiring immediate attention (Chapter 4, p.12); important long-term issues (p.20); data products considerations (Chapter 5); and an outline of the initial observing system (Chapter 6). Appendix 1 highlights important users of information on terrestrial carbon. Appendix 2 contains information on the relevant current observation programmes and activities.

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Motivation for carbon cycle observations

AMONG THE MANY MOTIVES FOR INTEREST IN THE CARBON CYCLE (POLICY, ECONOMIC, SCIENTIFIC, MANAGEMENT, SUSTAINABLE DEVELOPMENT, PUBLIC/SOCIETAL), THREE PROVIDE COMPELLING REASONS FOR THE ESTABLISHMENT AND OPERATION OF GLOBAL, SYSTEMATIC, LONG-TERM OBSERVATIONS OF THE CARBON CYCLE AND THE ASSOCIATED ASPECTS IN THE TERRESTRIAL AND ATMOSPHERIC DOMAINS:

Policy imperative for a global carbon observing system has been well established.

Through international negotiations, national governments have agreed to numerous conventions and multilateral agreements that specify or imply the need for carbon cycle information and therefore systematic, long-term observations. At the present time, the relevant conventions include: the United Nations Framework Convention on Climate Change (UNFCCC) and the associated Kyoto Protocol; the Convention on Biological Diversity; the Convention to Combat Desertification; Agenda 21 (agreed to at the 1992 United Nations Conference on Environment and Development); and the Global Plan of Action for the Protection of the Marine Environment from Land-Based Activities. These and other conventions identify needs and objectives to be satisfied through coordinated international efforts.

To meet their obligations under the conventions, national governments and international organizations need sound, consistent information on the terrestrial and atmospheric aspects of the carbon cycle and the factors that affect it. For example, land cover and use as well as their changes are essential to most of the conventions. Conventions require assessments of the current status, detection and projection of trends, and the implications from a policy perspective. Such evaluations are conducted for example by the Intergovernmental Panel on Climate Change in response to policy needs, based on published results of analyses that in turn depend on systematic global observations. It should be noted that the conventions also make provisions for observations; for example, UNFCCC (COP 5) has called on Parties to undertake systematic observation and research. UNFCCC requires transparent and verifiable reporting, and this will likely also apply to the Kyoto Protocol. A globally consistent, data-based approach such as proposed for the terrestrial carbon theme (Chapter 4) is well suited to satisfy this requirement.

It is important to note that while recent policy discussions have concentrated on the potential role of specific terrestrial sinks, the fundamental policy issue is the impact of increasing atmospheric concentration of trace gases. The increase depends on the uptake by the entire biosphere and is modulated by local land use actions. Improved understanding of the carbon cycle also necessitates consideration of the biosphere as a whole (IGBP Carbon Working Group, 1998; see also below). For these and other reasons, the proposed concept for terrestrial carbon observation (Chapter 4 and 6) encompasses the entire terrestrial biosphere and its interaction with the atmosphere. It also addresses the land use-dependent sink/source role of the biosphere through land cover and land use products at appropriate spatial scales (p. 12), thus providing the framework for ecosystem-specific carbon estimates.

A well-established need exists for information on the biosphere to support sustainable development and resource management.

Knowledge of the carbon cycle, especially terrestrial productivity, has long been vital to manage the biospheric resources upon which human societies depend. Appropriate management is particularly important for countries whose economic and social structures depend on production or subsistence agriculture. This motivation becomes stronger as a large and increasing portion of the net primary production is employed in the economic sphere (~ 40%; Vitousek *et al.*, 1986), and is further strengthened by continuing concerns about the long-term sustainability of managed terrestrial ecosystems in the face of threats from salinity, soil impoverishment and erosion.

Terrestrial carbon information is thus important from both public and private enterprise perspectives, but with different emphases. From the public perspective, governments are seeking policy instruments (either administrative or financial) to improve land use and land management practice, reduce or reverse trends towards the degradation of natural resources, and lessen the impact of natural disasters such as drought. The design of these instruments depends on reliable, detailed observations and predictions about the linked cycles of carbon, water and nutrients upon which human use of the terrestrial biosphere depends. From the perspective of private enterprise, information is typically needed at a detailed and local level (for instance to manage a project for maximum productivity and minimum leakage of contaminants or to support carbon trading). However, larger-area information is also necessary to interpret local information and use it in strategic planning. The importance of the interplay between public and private institutions is clearly evident in the post-Kyoto developments, with financial implications for the management and trading of terrestrial carbon stocks.

Improved knowledge of the carbon cycle, its variability, and its likely future evolution is essential.

There are large uncertainties in the magnitudes and locations of carbon fluxes between the land, oceans and the atmosphere. Current observations indicate that on average, 55% of the released fossil fuel emissions accumulates in the atmosphere, and that the carbon removed from the atmosphere is roughly partitioned equally between oceanic and (mostly northern hemisphere) terrestrial systems. Also, land sinks are more variable from year to year, in response to climatic as well as human factors.

We presently lack the understanding and observations needed to close the annual carbon budget at the global level. Furthermore, it is not possible to unambiguously determine the spatial (geopolitical) distribution of carbon sinks, and previous attempts to do so have suffered from an inadequate data base. Remedial programmes are being established in some regions; while these are important steps, they cannot take the place of a coordinated global observing system. Based on recent international research activities, it is evident that further progress in our understanding of the global carbon cycle and its likely future evolution depends on improved observations of the terrestrial carbon processes. For example, in a special issue reporting results of an IGBP model intercomparison, Cramer and Field (1999, p. iv) stated "…At the heart of these (efforts) are enhanced experimental and monitoring systems (flux measurements, satellite sensors, field and laboratory experiments, global data archives) which are being identified by every single paper in this collection as being important for better parameterization of terrestrial biosphere models". Improvements in models of the carbon cycle are essential for better projections regarding its behaviour, a critical pre-requisite for future policy discussions and measures. Conversely, improved understanding of the carbon cycle and the resulting models will facilitate increases in the efficiency and effectiveness of the observing systems and reporting procedures.

In addition,

Capability to observe key components of the carbon cycle and its dynamics has been established.

The capabilities for making atmospheric, ocean, and terrestrial carbon cycle observations have grown dramatically over the last 20 years. Global and regional atmospheric trace gas concentration measurement programmes have been operating for many years, and the quantity and quality of measurements has been steadily improving. In the terrestrial domain, similar advances in satellite remote sensing have led to global and regional products of land cover, fire, and measures of vegetation productivity. National and regional terrestrial networks are working through GTOS and FLUXNET to achieve consistent worldwide coverage. In parallel, numerical models of combined atmosphere-ocean-land system have advanced rapidly, keeping pace with the increasing speed and capacity of super-computing technology. Effective use and further improvements of these models directly depend on systematic global observations.

3

The IGOS Carbon Cycle Observation Theme

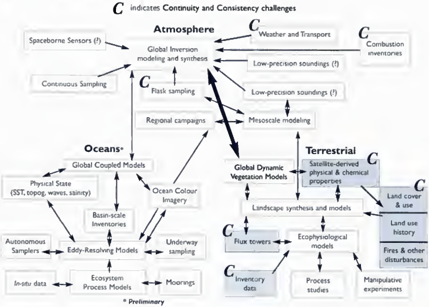
OVERVIEW

THE VISION FOR A CARBON CYCLE OBSERVING SYSTEM IS TO CONTRIBUTE TO THE INTEGRATED UNDERSTANDING AND HUMAN MANAGEMENT OF THE CARBON CYCLE THROUGH SYSTEMATIC, LONG-TERM MONITORING OF THE EXCHANGES OF GREENHOUSE GASES BETWEEN THE LAND, ATMOSPHERE AND OCEANS, AND THE ASSOCIATED CHANGES IN CARBON STOCKS. To achieve this vision, an observing system is required which synthesises information from several types of measurements: concentration of atmospheric CO_2 and other gases, surface flux observations and other *in situ* measurements, and satellite remote sensing. The combined monitoring system will yield estimates of CO_2 sources and sinks at multiple spatial and temporal scales from global to those relevant to land-use policy and resource management. These estimates should be provided with greatly reduced uncertainty relative to current practice, by designed expansions of current measurement networks and by systematic cross-checking of independent approaches.

The elements of such a system include measurement programmes on land, in the ocean, and in the atmosphere (Figure 1). It is based on local-scale measurements of the processes that control CO_2 exchanges between the atmosphere and the Earth's surface, and recognizes the crucial importance of models and other scaling algorithms to extrapolate to representative regional and global scales. The system includes multiple comparisons between predictions made by process models and larger scale observations, making it possible to disprove results of models that diagnose and predict large scale fluxes. This falsifiability is a necessary condition for a confident prediction of future atmospheric CO_2 levels. At the global scale, changes in atmospheric CO_2 are the benchmark against which all process models must be tested. This constraint can improve quantitative process model estimates only if applied regionally. An integrated observing strategy includes the application of multiple constraints at various spatial scales, taking advantage of process-based research, the ability of satellite data to map heterogeneous properties of the surface features, and the averaging properties of the atmosphere to quantify CO_2 fluxes over large areas.

Ultimately, an integrated observation strategy should provide timely diagnosis of carbon sources and sinks at high resolution in both space and time that simultaneously satisfies all the observations/data constraints at multiple scales. Such an observing system will be more than a set of observations. Observations alone can characterize processes at local scales, and can constrain overall mass balances at the

Figure 1. Observing the Global Carbon Cycle



largest scales. Models ingesting data from spaceborne sensors must be used to extrapolate local understanding to regional scales. The goal is to build a system of data and models at multiple scales that is designed to contain enough overlap to allow sufficient cross-checking to permit robust estimates of fluxes and their underlying causes. The results obtained in this manner will be the best possible at a given time, constrained by the quality of the observations and the understanding of the carbon cycle processes that is embedded in the models. The evolution of the overall system will necessarily be a gradual process which achieves two principal tasks: serving the current needs of the user communities, and improving the comprehensiveness and quality of the observations and of the models so that the future needs of users may be met more effectively.

To achieve the above vision, an approach encompassing all three domains of the global carbon cycle must be adopted, as envisioned in IGCO (Steffen, 2000). The present report focuses on the atmospheric and terrestrial components, both of which are necessary to meet the terrestrial domain objectives (p. 12). The two principal links between the terrestrial and oceanic domains are the atmosphere (covered in this report), and water transport (surface and subsurface) which will be fully developed within IGCO.

Many of the elements of a terrestrial carbon observing strategy are now in place or under development. The challenges are to ensure that important existing observations continue and key new observations are initiated; to identify activities and agencies willing to contribute to establishing global carbon observations; to build in appropriate overlaps and leverage among the disparate data sets, thus filling important data gaps; to design and implement linkages among components, activities and contributions; and to link observation and research programmes so that the ongoing improvements in observations and products are made in an optimum fashion. An overarching requirement is the integration of the terrestrial/atmospheric observations with ocean observations within the IGCO; in this respect, this report will provide the input on behalf of the two domains. Rolling requirements review (WMO, 2000) can be used as an effective tool to guide future evolution of the integrated system.

CURRENT STATUS

Previous interests in the carbon cycle have been primarily economic in nature and is mostly related to land or ocean ecosystem productivity. In recent decades, the scientific interest in the carbon cycle has intensified, driven by the need for improved understanding of the role of carbon in the total earth system. Thus, the existing observing systems are primarily a combination of national resource-based inventories and scientific programmes with observation components at various levels, from national to global. Traditional national inventories have evolved generally independently, based on perceived national resource development needs. The strong interest by countries in the broader aspects of the carbon cycle is recent, and has been stimulated by the concerns about the role of trace gases in climate change.

Questions related to components of the carbon budget (such as land productivity) have been important to international reporting organizations such as UNEP, FAO and others. Traditionally, these agencies have relied on summarized data obtained within countries. In some cases, additional data were obtained directly to meet specific needs, e.g. by FAO for forest resources assessment. In the 1990s, global observing systems have been established for climate (GCOS), terrestrial ecosystems (GTOS) and oceans (GOOS) that require carbon cycle information to meet the needs of their clients. They all have, or are in the process of establishing initial observing systems based on current capabilities (Appendix 2). The global observing systems benefit from previous developments regarding existing systematic, long-term observations in two areas: observations of some processes and variables that affect the carbon cycle (e.g. weather, state of the atmosphere); and certain aspects of the carbon cycle which have been subject to research for a long time (e.g. plant growth).

In this section, the current status of carbon observing systems is briefly reviewed, including back-

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[1] http://www.cmdl [illegible]

ground information on products and users of the observing systems' outputs.

Atmospheric observations

Current atmospheric trace gas concentration measurements are sponsored by numerous countries, in most cases as part of research programmes. These data have made pivotal contribution to the awareness and understanding of the climate change issue; in particular, the Mauna Loa data series is now arguably the best known data set in earth sciences. The impetus for the work done by the many cooperating organizations and institutions is to make atmospheric measurements of trace gas species that will lead to better understanding of the processes controlling their abundance. Aiming to overcome accuracy and consistency problems in these measurements, GLOBALVIEW-CO_2 was established as a cooperative atmospheric data integration project. GLOBALVIEW - CO_2 is a data construct presently involving approximately 17 organizations from 13 countries[1]. An internally consistent 21-year global time series has been compiled so far.

Monthly average data from the individual networks are also available via the WMO World Data Center for Greenhouse Gases, Tokyo and the Carbon Dioxide Information Analysis Center, Oak Ridge. The key users of these data are global carbon cycle modellers who derive CO_2 sources and sinks distribution through inversion methods (top down approach; p. 12). Among the most significant impacts of the network to date has been the discovery of unexpectedly large uptake of CO_2 by terrestrial ecosystems at temperate latitudes in the northern hemisphere. However, due to the sparseness of the current network (p. 19), there is potential to misinterpret the derived source/sink scenarios.

In addition to CO_2, the observing system includes measurements of $\delta^{13}C$ and $\delta^{18}O$ in CO_2, CO, and the O_2/N_2 ratio. These measurements are used for deducing the mechanisms responsible for fluxes in inverse modelling: δ13C and O_2/N_2 are used to distinguish terrestrial from air-sea exchange, $\delta^{18}O$ is used to estimate gross primary production (as opposed to net ecosystem exchange). Measurements of other trace gases related to combustion (e.g. CO, CH_4, H_2, and VOC's) are used to estimate the anthropogenic contribution. Careful inter-calibration among measurement laboratories and sampling programmes is essential for these data to be most valuable.

The current atmospheric observing networks focus on measurements in the remote marine boundary layer, to avoid contamination by local sources and sinks. The data are invaluable and an essential starting point, but many studies have highlighted the need for additional measurements over the continents. These are problematic because of the strong variability in both space and time, so new sampling strategies will need to be formulated (p. 23). Observing system simulation with models will be required for network optimization.

Terrestrial observations

Traditionally, the exploitation of biomass resources has been the main reason for terrestrial carbon observations, motivating many countries to establish operational inventory or monitoring in support of sustained use of forests, cropland and grasslands. These programmes differ in purpose, coverage and duration. National forest inventories, underway for decades (up to 1930s) in many temperate and northern countries, have emphasised harvestable timber (above ground woody biomass) as the main component of interest and have focused on forests with commercial potential. They have been carried out at national, subnational and local (by commercial operators) levels. Various designs have been implemented, employing permanent or variable sample plots, aerial photographic interpretation, and cruising techniques. For the most part, these programmes have not been coordinated internationally. In spite of these differences and other deficiencies, the inventory data bases provide unique historical information on forest and land use carbon dynamics, especially in view of the decadal or longer time scales.

For agricultural and rangeland ecosystems, regular yield/aboveground biomass production surveys have been established in various countries, either nationally or sub-nationally for specific crops.

[2] http://www.fao.org/WAICENT/FAOINFO/ECONOMIC/ESS/2000/2000.htm

National reports have been provided to FAO for many years[2]. Coarse estimates of soil carbon content can be derived from data embedded in national and regional soil mapping programmes, but the quantitative accuracy of this information is inadequate for carbon inventories (p.12 and p.20). Geo-referenced quantitative soil carbon data are available from SOTER (e.g. 4000 estimates in the global WISE soil profile database, 1700 estimates are available for Latin America, 800 for Eastern Europe) but these are too sparse to allow precise global or regional estimates.

In parallel to operational inventories, national research programmes have also initiated long-term observations addressing various aspects of terrestrial ecosystems, and these programmes have gradually become correlated at the international level through the efforts of the scientific community or international organizations. At the present time, numerous large-scale programmes exist that are relevant to carbon cycle observation at global to national levels. In general, such programmes have been based on site measurements, but larger area coverage has become more frequent over time and satellite observations have recently become a key observation tool.

Appendix 1 provides a sample of current programmes that require information on the terrestrial carbon cycle. Website references to specific programmes have been included to document the actual existing needs and the breadth of the user community. The requirements differ in coverage (global, continental, national); type of product; and the user group. It should be noted that for some activities, national agencies also require consistent information beyond their territories.

Appendix 2 lists some of the existing observing networks and programmes. Only examples of international or worldwide *in situ* networks are included. For satellite observations, Appendix 2 also lists products generated at the present or planned for the near future. So far, most of these satellite products have been prepared for research purposes or are experimental in nature. Nevertheless, they are frequently produced in multi-year series, and retrospective reprocessing is employed to improve the product characteristics.

In addition to the above acquisition and product generation programmes, a number of projects have been undertaken that contribute to the development of systematic global observing capabilities. They include the GOFC project initiated by IGOS in 1997[3]; World Fire Web, designed to provide biomass burning products[4]; the IGBP NPP inter-comparison project, contributing to the improvement of algorithms for ecosystem productivity estimation (Cramer and Field, 1999); the GTOS NPP project[5]; and others. Also important are numerous research projects undertaken as part of satellite programmes (Appendix 3), many of which are global in scope and include product development, validation, and product generation activities.

The development of consistent *in situ* observation programmes has been a significant challenge for GTOS and other IGOS Partners. FLUXNET and ILTER (Appendix 2) are presently the most consistent and quantitative networks at the global level, and the expansion of ecosystem flux measurements has been advocated by GCOS at the SBSTA/COP forum[6]. Harmonization of regional *in situ* observation programmes is being addressed by GTOS as part of the GT-Net (Appendix 2). Some research programmes are addressing harmonization of data collected nationally, e.g. a N.A./Asia comparison of national forest inventories is being carried out.

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[3] http://www.gofc.org

[4] http://www.gvm.sai.jrc.it/

[5] http://www.lternet.edu/gtnet/

[6] http://www.unfccc.de

4

Challenges for carbon cycle observations

THIS SECTION DISCUSSES THE APPROACH TO DEVELOPING A CAPABILITY FOR SYSTEMATIC, LONG-TERM OBSERVATIONS OF THE TERRESTRIAL AND ATMOSPHERIC COMPONENTS OF THE GLOBAL CARBON CYCLE. The guiding considerations are: establishing long-term goal and vision; building on existing capabilities; ensuring continuation of existing essential activities, then seeking enhancements; and ensuring close interactions between research and observation specialists.

In developing the list of key challenges, the following assumptions have been made:

1. Current satellite missions will achieve or exceed their planned lifetime.
2. Presently approved satellite missions will be successfully put into operation.
3. Cooperation between research and observation programmes and organizations is an effective way to establish systematic, long-term observing capabilities.
4. Existing efforts aimed at improving the spatial resolution of meteorological and hydrological information will continue, especially with respect to precipitation and near-surface temperature fields with a high spatial resolution (needed by ecosystem models). This includes liquid and solid precipitation (including satellite missions such as Tropical Rainfall Measuring Mission [TRMM], Aqua) and numerical weather prediction (NWP) or NWP reanalysis projects. These issues are addressed in satellite observation programmes for weather and climate forecasting purposes (by WMO and national meteorological agencies) and by research programmes such as World Climate Research Programme (WCRP).

5. Only ongoing, repeated observation requirements are of concern to this report. Thus, baseline data products (e.g. soil type maps) are not considered here (refer to Cihlar, Denning and Gosz, 2000).

The strategy for the carbon cycle observation is based on a combination of methods. To understand the importance of the various observations specified on pages 12 and 20, the observation approach is briefly described below.

THE CONCEPT

The policy community requires information on spatial and temporal patterns of terrestrial CO_2 flux at high resolution and over large areas (Chapter 2). These requirements imply the use of ecosystem process models linked to spatial measurements that are available everywhere, such as from satellites (p.31). Satellite data can also provide up-to-date information frequently, in relation to the rate of change of the variables of interest. In this 'bottom-up' strategy, local land processes are scaled-up in space and time using satellite imagery and other spatial data. The primary limitation of this approach is the difficulty of conclusively establishing the accuracy and reliability of the scaled-up estimates. In addition, the success of the approach depends on the availability of reliable models that represent all the important processes affecting CO_2 exchange with the atmosphere, including the impact of various land-use measures. Such models are not yet available for all processes, although inventory-based methods and conversion tables currently provide an acceptable approach (IPCC, 1996). An alternative and complementary method is to analyse the carbon budget of the atmosphere from a mass balance point of view ('top down'). Such an analysis is predicated on the availability of atmospheric concentration data and other inputs, and it can be carried out in several spatial and temporal domains. Both approaches have been used in various studies.

Used synergistically, the 'top down' and 'bottom up' approaches take advantage of their strengths to compensate for their respective weaknesses (Cihlar, Denning and Gosz, 2000). This may be achieved through atmospheric inversion methods (e.g. Ciais *et al.* 1995) or through a multiple constraint approach. In the latter, the various data sources are employed to constrain the process parameters in a biosphere model, so that the model predictions are consistent with all available observations (Figure 1). The essence of the approach is to constrain the model parameters to optimal values using inversion theory, and thus to infer the complete space-time distribution of carbon stores and fluxes. In practice, the model predicts the observed variables at locations where measurements (surface- or satellite-based) are available, and then finds the parameter values that minimize the overall difference with the measurements. Although more complex, the multiple-constraint approach offers the possibility of employing multiple types of data with very different spatial, temporal and process resolutions. The predictions of a multiple-constraint approach are subject to verification by confronting the model with a wide range of data sources representing various spatial scales. Failure to accommodate all data streams simultaneously with a common parameter set enables finding model errors, thus preserving the scientific integrity of the approach. It should be noted that the availability of diverse observations is essential to avoid answers that meet the acceptance criteria but may be incorrect due to insufficient data.

After combining the bottom up and top down techniques, the spatial distribution of carbon sources and sinks is produced with high spatial and temporal resolutions, and of the best quality possible with the available observations and understanding of the carbon cycle. The spatial and temporal resolutions will then be constrained by the resolutions of the input satellite (and other) data. This approach is also fully compatible with reporting needs for small areas (such as may be required for the Kyoto Protocol), although additional data may be necessary to fully meet the reporting requirements depending on the case.

THE LONG-TERM CONTINUITY AND CONSISTENCY CHALLENGE

This section describes the most important and urgent issues that IGOS Partners face in establishing systematic, long-term observations of the terrestrial and atmospheric components of the global carbon cycle. The discussion presents only the key observation requirements that are needed on a sustained, long-term basis; a complete list of observation requirements is available elsewhere (Cihlar, Denning and Gosz, 2000). Following a brief discussion of each item below, the key issues are identified. The 'issues' represent items that need to be addressed now in order to ensure continuity of existing observations and output products, or they are essential improvements that must be made to balance the effectiveness of the individual observing system elements. In all cases, the observing technology exists, and in most it is deployed at least partly.

This section contains only the specific areas that need attention in implementing an initial observing system. Refer to Chapter 6 for a more complete description of the initial system (see also page 8 and Appendix 2).

A. Terrestrial

Information on land characteristics is required to determine the spatial and temporal distribution of terrestrial carbon sources and sinks. This information is needed at a range of spatial and temporal scales, and is used to run biospheric models and to determine the accuracy of the model outputs. The major types of information needed are described in the next sections.

Land cover and land use

A primary characterization of land cover, and monitoring its changes, is fundamental for carbon cycle observation and assessment, but also to nearly every aspect of land management. Like-wise, observations of land use and land use change are fundamental to an understanding of the human impacts on the biosphere. Because of the need to span a range of spatial and temporal scales, land cover and use are ideally suited to satellite-based observation with various sensors. Many years of experience have clearly demonstrated the capability of data from moderate and fine resolution earth observation satellites to be classified into a wide range of products that have been highly valuable in providing a synoptic view of the earth, leading toward more sustainable use of earth resources. Global scale land cover classifications have been produced using AVHRR data (available since 1983).

Data from ATSR/ERS-2 (1996) and VEGETATION (1998) have been used successfully to map land cover at continental scales and detailed plans are in place for their use globally. AVHRR data have also been employed to estimate vegetation cover characteristics which are important to full carbon accounting, including leaf type (broadleaf vs. needleleaf), leaf longevity (evergreen vs. deciduous) and canopy cover. The improved data now available from MODIS, MISR, MERIS and AATSR are expected to yield improvements in classification accuracy, detail and characterization. In the longer term, the planned NPP, ADEOS-II/GLI, GCOM-B1/SGLI and NPOESS missions will provide follow-on medium resolution calibrated optical data. The spatial resolution will improve from the recent ~1000 m to ~ 300 m but the continuation of such spatial resolution capability is not ensured, nor has its necessity been conclusively established (see page 21/land cover). In the microwave domain, satellite SARs on Japanese (JERS, ALOS), ESA (ERS) and Canadian (Radarsat) platforms provide land cover information in perennially clouded areas.

At regional to landscape scales, Landsat (since 1973), SPOT (1986) and similar sensors provide land cover with the necessary spatial detail. The spatial coverage of high resolution mapping applications is rapidly growing, and the production of continental and global maps is envisaged to be generated in the near future (GOFC Design Team, 1999). Regarding classification schemes, an agreement has been reached on the highest level classes of land classification schemes. Initiatives such as the FAO's Land Cover Classification System offer a hierarchical approach which allows easy upscaling of detailed land cover classifications from national to global. Similarly, a strategy has evolved to produce intermediate products that can be easily converted into a land cover classification scheme by a particular user (GOFC Design Team, 1999). Much experience has also been gained on the use of coarse resolution land cover classifications for stratification supporting statistical samples of high resolution images subsequently used to quantify rates of change.

Land use is a critical carbon cycle parameter. The knowledge of present and historical (decades to centuries) land use is essential to properly represent carbon exchanges in models. Present land use can be obtained by combining satellite-derived land cover and *in situ* observations such as statistical reports. Ancillary evidence from satellite images can provide supporting evidence as well; for example, the appearance of logging roads provides a strong indication of particular forms of land use. FAO has estimated that given sufficient resources, a global land use map at the 1:1million scale could be produced in 3-5 years. Historical land use may be derived from existing land-use records (e.g. Ramankutty and Foley, 1992). The process of convergence on land cover products is advanced but not completed, and while the observations required for land use products are well understood, the classification approach is less advanced.

The continuity and consistency issues are:

1. **[*sat*]**[7] Continuity of calibrated, fine resolution optical data from both fixed-view (Landsat type) and pointable (SPOT-type) sensors needs to be ensured. Similarly, continuity of complementary SAR data needs to be assured. These observations should be accompanied by a consensus strategy for global satellite data acquisition at high resolution (see also Rosenqvist *et al.*, 1999).
2. **[*sat*]** Institutional arrangements need to be made for product generation and quality control, possibly through the GOFC project, and the development of highly automated methods and products for land cover classification should be encouraged.
3. **[*sat*]** Archived satellite data (both coarse and fine resolution, optical and microwave) are a very important and often unique source of information on land cover as well as other attributes (fire, seasonal growth cycle). In many cases, these data have not been processed, or have been processed using algorithms that are presently obsolete. Therefore, reprocessing of satellite data to prepare time-stamped or time series products should be systematically addressed. In the context of the Kyoto Protocol, the state of land cover in 1990 and changes since that time that have special significance.

Above and below-ground biomass

Estimates of above- and below-ground biomass provide fundamental information on the size and changes of the terrestrial carbon pool as land use and associated land management practices change. Observations of biomass components have a rich history associated with human needs for food, fibre, lumber, and other biomass products. However, there are large gaps in these data in terms of (i) inclusion of above and below ground components, (ii) spatial and temporal consistency, and (iii) completeness in both spatial and temporal dimensions. Carbon cycle science and consequent policy decisions now depend on partial observations from research studies, from inventories focused on commercial interests such as forest inventory or crop yield surveys, and broader surveys or compilations, e.g. country-level statistics assembled by FAO.

Most of the detailed *in situ* data are not readily available or are only available as highly aggregated summaries. National forest inventories, available for recent decades in many temperate and boreal countries, provide a potentially rich data source but their use requires careful analysis and interpretation. At present, remote sensing provides high resolution global coverage of land cover and cover changes (The concept, p.12) which are also relevant to the estimation of above- ground biomass, but there is no satellite-based capability to estimate biomass directly. Future satellite measurements, e.g. from lidar (ESSP VCL, ICESat GLAS), will provide information on forest height and structure, thus allowing detailed and robust biomass estimates globally. However, the below ground component cannot be obtained from satellite platforms; it requires an increased density of *in situ* observations and improved scaling algorithms (see Terrestrial, p.21).

The existing inventory data, though limited in scope and completeness, have an important role to play. In case of forests, with careful interpretation these inventories can provide estimates of the total forest sink or source, rates of deforestation and regrowth, and losses to disturbance and harvesting. They yield direct estimates of carbon changes associated with forest area or age structure but only partial information on effects of growth rate due to climate change, N deposition etc. Since many countries have conducted forest inventories since the 1930s or even earlier, the inventories provide an important link between current and past effects (see Terrestrial, p.21).

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[7] **sat** – primarily a satellite observation issue (implementation, development, or research

Depending on the resolution of the Kyoto Protocol reporting requirements, there will likely be a need for repeated measures of biomass/carbon density with high degree of accuracy for small land parcels. Traditional forest survey methods may meet this need, but satellite sensors such as profiling lidars are expected to offer an important additional and consistent information.

Regarding below-ground biomass, the FAO/UNESCO soil map of the world (based on soil surveys carried out during 1960s; FAO, 1995) remains the only global inventory of soil information to date. Coarse resolution soil carbon density information has also been derived using this map[8]. Several regional updates of the global map have been undertaken using the SOTER approach (FAO, 1993). These updates contain georeferenced analysed soil profile information with quantitative soil characteristics, including soil carbon. Under preparation are SOTER products for Southern Africa and for Western Europe; the global update is expected to be completed by 2006, subject to resources being available for West Africa and Southeast Asia segments. In addition, ISRIC and FAO have compiled >4000 georeferenced soil profiles that include carbon data and have been used to provide the best estimates to use for soil properties including soil carbon for each mapping unit (Batjes *et al.*, 1997). National holdings of georeferenced soil profile information are of variable quantity and quality, and some are difficult to access given stringent copyright rules (Nachtergaele, 2000).

The continuity and consistency issues are:

1. ***[sat]*** Above ground: ensure ongoing availability of canopy structure measurements from satellite sensors, beyond the planned ESSP VCL mission. The best current prospects are lidars and advanced SARs (see also Terrestrial, p.21).
2. ***[ins]***[9] Below ground: increased density of *in situ* observations (i) by improving or adding observations within existing networks; (ii) by significantly expanding the soil profile databases available through SOTER and similar programmes; and (iii) through more efficient use of national inventories, in combination with land cover derived from satellite data (refer also to Terrestrial, p.21).

Seasonal growth cycle

Seasonal growth characteristics such as leaf area, growing season duration, and timing of growth (onset and senescence) provide strong constraints on carbon sequestration (Cramer and Field, 1999). Many ecological/carbon models require leaf area index (LAI) and, more recently, information on vertical and horizontal leaf distribution to account for different light use efficiencies of sunlit and shaded leaves. LAI is typically obtained from passive optical measurements, using empirical or model-based estimates calibrated by ground measurements. Satellite-based LAI products have been generated globally as well as for specific regions from AVHRR data, and they are planned to be produced globally by Terra. A coordinated LAI validation programme has been initiated under CEOS WGCV. Simple indices from passive remote sensing (e.g. NDVI), while giving reasonable first order estimates tend to saturate at LAI≈4 depending on canopy type, structure, and leaf state. Adjustments have been developed but intelligent methods are required to extend the maximum estimable range of LAI. Multi-angular measurements from sensors such as MISR, POLDER and EPIC offer strong potential in this respect even though the latter two are limited by their spatial resolution (~10 km). Although further development needs to be undertaken (see Terrestrial, p.21), the evidence of the importance of multi-angle measurements (Knyazikhin *et al.*, 1998) is sufficiently strong to justify the requirement for their continuity in support of LAI products.

Depending on the biome, the growing season is limited by temperature (temperate and boreal) or moisture (tropical). In addition, the onset of both green-up and senescence varies with species within plant assemblages. Satellite observations have shown the ability to detect green-up and senescence in ecosystems. While such observations are valuable, reliable determination of growth season duration, whose inter-annual variation is on the order of days, requires calibration and cross-comparison of methods from ground-based meteorology and space. For temperature-limited ecosystems, it has been shown (Frolking *et al.*, 1999) that SAR measurements are a sensitive indicator of freeze-thaw transitions.

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[8] http://www.daac.ornl.gov/SOILS/igbp.html

[9] **ins** = primarily an in situ observation issue (implementation, development)

The continuity and consistency issues are:

LAI:

1 **[*sat*]** Ensuring continuity of moderate resolution optical sensor measurements: same as for land cover (Land cover, p. 12).
2 **[*sat*]** Ensuring continuity of multi-angular sensor measurements of the MISR type.
3 **[*sat*]** Ensuring agency commitments to generating global LAI products beyond the MODIS/Terra period.

GROWING SEASON DURATION:

1 **[*sat*]** Ensuring continuity of moderate resolution optical sensor measurements: same as for land cover (Land cover, p. 12)
2 **[*dev*]**[10] Performing calibration and cross-comparison of products from ground-based meteorology and satellite-based, including sensitivity analysis of the space-based estimates over long periods and an assimilation strategy employing data from multiple satellites (AVHRR, VEGETATION, MODIS, ATSR).

Fires

In many regions of the world, fire causes the strongest disturbance of vegetation. Worldwide information on fire is necessary to calculate net carbon sink, and fire may be a major cause of the large observed inter-annual variations in carbon emissions from ecosystems. Fire is also a very important factor influencing ecosystem succession and land use. Information about the fire timing, areal extent, intensity, and trace gas emissions has many societal implications beyond the carbon cycle (Ahern *et al.*, 2000). Among these are health implications of major fire events; the effects on timber and range resources; and the risk to lives, valuable economic infrastructure, and private property.

The status and needs for global biomass burning were determined in a 1999 GOFC workshop (Ahern *et al.*, 2000). Large fires in forests and grasslands, which are most important for the carbon cycle, can be detected using satellite-based thermal and optical sensors. Clouds prevent detection of a significant fraction of fires, but statistical corrections can be applied to obtain reliable estimates of the location and timing of fires. Recent work with SAR shows considerable promise for burnt area detection. The area burned in large fires can be mapped with good accuracy using satellite data, notably ATSR on ERS-1 and -2, VEGETATION on SPOT-4, and MODIS on Terra. Prototype burned area products from these sensors will be produced by ESA/ESRIN, JRC and NASA and the development of community consensus algorithms is underway. The continuity of optical data is assured through the NPP, ADEOS-II, GCOM and NPOESS missions. However, the planned sensors do not have the preferred spatial resolution (~200 m, Ahern *et al.*, 2000). Further assessment of this spatial resolution requirement is needed (see also on page 21 land cover). Smaller fires can be mapped, when needed, using fine resolution sensors such as Landsat and SPOT; these sensors also can also provide more accurate information on the spatial distribution of fires and for more accurate area estimates through double sampling approaches. Historical information on area burned is important to estimating secular changes in fire frequency. The most promising approach is through reprocessing of the AVHRR archive (1982-2000).

A network of receiving and processing facilities, the World Fire Web (WFW) led by the Joint Research Centre of the European Commission, is nearing completion[11], and will provide global coverage of active fires as well as burned areas by the end of 2000. However, this is a demonstration project and there is no assurance that this capability will be maintained into the foreseeable future. An important global outlet for fire information is the Global Fire Monitoring Centre, operated for the United Nations by the University of Freiburg[12]. It collects fire information worldwide and provides it in a consistent format, as well as providing critical analyses to help national and international agencies develop more effective approaches to fire management.

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[10] **dev** = primarily a research and development issue

[11] http://www.gvm.sai.jrc.it/fire/wfw/wfw.htm

[12] http://www.uni-freiburg.de/fireglobe

The continuity and consistency issues are:

1 ***[sat]*** Making commitments to the continuity of fire products generation (WFW, GOFC) and to reprocessing the archived AVHRR data to obtain a global fire history (as an input to estimating the current C fluxes).
2 ***[sat]*** Ensuring long-term operation of the World Fire Web project.

Solar radiation

Global solar radiation (shortwave, SW) and its photosynthetically active radiation (PAR) component are major drivers of surface processes such as photosynthesis and evapotranspiration. Global long term monitoring is required for providing inputs to terrestrial photosynthesis models (Cramer and Field, 1999), and for a variety of agrometeorological applications. For carbon uptake modelling, daily PAR estimates are needed at a resolution of 50 km (minimum) to 10 km (preferred). Several methods have been developed to derive SW from satellite radiance measurements (Charlock and Alberta, 1996). Global data set of monthly averages of SW have produced for climate purposes using ERBE data by the NASA Langley Research Center for the GEWEX Surface Radiation Budget Project (SRB[13]); Version 2 (global, 1° resolution, 3-hourly, 1983-95) will be completed in 2001. The products generated so far are the result of various research programmes. Estimates of PAR averages at weekly and monthly time scales can be derived as a constant fraction of SW. The limitations of these products are coarse spatial and temporal resolution, and their availability for a limited period only (to 1995).

The continuity and consistency issues are:

1 ***[sat]*** Ensuring commitment to the development and routine production of daily to monthly SW products for the period beyond 1995 and ongoing for the future, at the highest feasible spatial resolution.

Surface-atmosphere fluxes

Ecosystem flux measurements are a critical element of a terrestrial carbon observing system. The data provide essential input to process studies, the development and testing of models, and to upscaling from sites to regions (Cihlar, Denning and Gosz, 2000). Fluxes of carbon, water and energy are continuously measured with sub-hourly time steps at 140 stations worldwide (30 of which have data for >3 years) encompassing a range of terrestrial ecosystems and climate. Data are collected in regional networks (CarboEuroflux - Europe, Ameriflux – North America, LBA – South America, Asiaflux - Japan, Thailand, Ozflux- Australia) and analysed as synthesis products within the framework of FLUXNET. The current network design provides useful data for model and remote sensing products validation at the scale of 1km as well as insights on biome-specific responses to environmental factors and their temporal and spatial variability (Valentini *et al.*, 2000).

The continuity and consistency issues are:

1 ***[ins]*** Maintaining the existing flux measurement programmes for at least 10 years at a site. These measurements are essential to capture the seasonal and inter-annual variability.
2 ***[ins]*** Expanding the current network (i) in under-represented regions (especially Africa and Asia), and (ii) in ecosystems undergoing major disturbances or highly dynamic responses (complex and highly disturbed landscapes; after fire regeneration, logging, degraded lands, grasslands, savannas; across gradients of succession, stand age, and land-use intensity).
3 ***[ins]*** Operating a selected set of long-term 'ideal' stations for monitoring carbon, water and energy fluxes on representative biomes where disturbances, and direct human impacts are minimal, to serve as anchor stations for understanding climate variability.
4 ***[ins]*** Improving international coordination with online data transfer to a centralized facility, responsible for data quality check/assurance, data assimilation, and synthesis products.

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[13] http://www.gewex.com/srb.html

Ecosystem productivity

Ecosystem productivity measures quantify carbon uptake by terrestrial ecosystems. Net primary productivity (NPP) is the net biomass increase through photosynthesis, while net ecosystem productivity (NEP) refers to net carbon exchange with the atmosphere after accounting for soil respiration and organic matter decomposition. Carbon remaining in the ecosystem is obtained as the difference between NEP and losses due to fires, insects, harvest and other disturbances. Together, these measures meet the needs of various clients, including those interested in climate change and in resource management (Cihlar, Denning and Gosz, 2000). Ecosystem productivity quantities are determined using satellite-derived products (see pages 12-17); soil and meteorological data bases; and biogeochemical models that mimic the ecosystem processes involving carbon uptake and transformations within the ecosystem as well as the exchange with the atmosphere. Surface-atmosphere fluxes (see page 17) and associated site observations are essential for the development and validation of the ecosystem models. To date, regional or ecosystem productivity products using AVHRR data have been generated by various groups at global and regional levels, using both top down and/or bottom up approaches[14]. Refinements of products and methodologies for both approaches are subject of intensive research, stimulated in part by the increased capabilities of the new satellite sensors. Core algorithms can be validated locally, but the behaviour of the models beyond the scale of eddy covariance towers is not well constrained a priori. Some measure of overall mass-balance constraint may be possible through airborne campaign sampling of trace gas concentrations in conjunction with mesoscale atmospheric transport modelling (Stephens *et al.* 2000).

The continuity and consistency issues are:

1 **[sat] [ins]** Ensuring commitments to providing the required data inputs (pages 12-17 and 19) and output products.

2 **[ins] [dev]** Expanding the *in situ* observation networks and obtaining data to improve the quality of satellite-derived products and the performance of biogeochemical models.

B. Atmospheric

The trend in the global mean concentration measured for the last 40 years is one of the most basic observations characterizing global change, and reflects the integral of all source and sink processes at the surface. Concurrent changes in CO, CH_4, O_2/N_2, and the stable isotopic ratios $\delta^{13}C$ and $\delta^{18}O$ in CO_2 as well as other trace gases provide important information about source/sink mechanisms. Nearly all of the data are collected by flask sampling in remote areas to capture variations in clean, background air far from local sources and sinks. In the past decade, the networks of sampling sites maintained by various governments have reached a spatial coverage sufficient to make inferences about sources and sinks on continental or ocean-basin scales in addition to the global-scale inferences that have long been made on the basis of trends, e.g. at Mauna Loa and the South Pole. This is accomplished by tracer transport inversion using wind and climate data collected by the weather forecasting infrastructure and numerical models of the transport of trace gases[15]. Inverse calculations from atmospheric data can provide valuable mass-balance constraints to the integral of surface exchanges estimated from "bottom-up" inventory and model or satellite-driven aggregation methods. This also requires accounting for the anthropogenic combustion source of CO_2, which is available from econometric inventories.

The current network provides only gross constraints on very large spatial scales. Network optimization studies have shown that adding additional observations, especially over the continents, would reduce flux uncertainties substantially (Rayner *et al.* 1996; Gloor *et al.* 2000). Airborne sampling and continuous monitoring have been shown to be particularly effective to achieve this aim. Augmenting the existing network with only stations in the remote marine boundary layer would require many more additional stations to achieve a similar reduction in uncertainty.

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[14] http://geo.arc.nasa.gov/sge/; http://www.ccrs.nrcan.gc.ca/ccrs/tekrd/rd/apps/em/beps/bepse.html

[15] http://transcom.colostate.edu

Long-term continuity

The current sampling system is operated by research funds from many agencies in over a dozen countries. Individual sites are thus subject to elimination due to unstable funding in many quarters, and issues of methodological consistency and interlaboratory calibration and standards make the use of the data difficult at the global scale. These difficulties are being addressed by an international voluntary effort to coordinate and ensure consistency among the many observing networks (GLOBAL-VIEW-CO_2, 2000[16]). This programme facilitates round-robin intercomparison of standard air among several laboratories, adjustments for calibration offsets among participating laboratories, filling and smoothing of the data record, and unified access to the data record across the many national programmes.

- **[ins]** The issue is commitment to ensure the long-term continuity and stability of the atmospheric sampling programme.

Calibration and accuracy

All measurements of atmospheric CO_2 are made relative to standards derived from the WMO primary standard linked to fundamental physical constants by high-precision manometric techniques maintained by the US National Oceanic and Atmospheric Administration. It is crucial to maintain these standards, generate high-quality secondary standards, and make them available to measurement laboratories in the many countries that participate in the observing network. This is expensive and difficult to achieve, and as long as this activity is funded by research funds there will be sacrifices made to support other worthwhile activities. Past difficulties in propagating standards to many laboratories have limited the overall effectiveness of the current networks. An immediate challenge therefore is to significantly improve the ability for all laboratories to link to the fundamental calibration scales. As part of its Global Atmospheric Watch (GAW) programme, WMO CO_2 measurement expert forums have identified 0.05 to 0.1 ppm as a target "network" precision for merging data from different laboratories in order to determine regional fluxes (Francey, 1997). More than 20 years of international effort has so far failed to consistently achieve this target. The effective spatial coverage with the current measurement sites is compromised by these calibration errors, as is the consistency of sufficiently long time-series for source attribution studies. These problems are even more serious for CO_2 tracers such as $\delta^{13}C$ and O_2/N_2. In all of these measurements, achieving high precision depends on repetitious alternating analysis of sample and reference air in a controlled environment and with a sufficient sample size.

Recent WMO (mainly for CO_2) and International Atomic Energy Agency (mainly $\delta^{13}C$) measurement expert forums have unanimously endorsed a global intercomparison strategy for greenhouse gas measurements (Francey, 1997). Called GLOBALHUBS, its first priority is to establish much more frequent, comprehensive and transparent comparisons between many more measurement laboratories than currently possible, and to incorporate this information into GLOBALVIEW for CO_2 and other species. Four globally distributed HUB laboratories are proposed which maintain and/or develop suites of standards (linked to primary standards), but also maintain intensive HUB intercomparisons using a variety of techniques, e.g. a highly precise low flow rate CO_2 system (see Atmospheric, p.23). The GLOBALHUBS programme requires initial set-up funding to obtain the needed hardware, to maintain or strengthen the links to primary standards, and to fund significant communications and processing development efforts.

- **[ins]** The issue is to ensure timely intercalibration of laboratories to the primary WMO standards with a goal of reducing interlaboratory differences in measured CO_2 concentrations to ≤ 0.1 ppm.

Expansion of the observing network

Estimation of sources and sinks at continental or ocean-basin scales by atmospheric transport inversions is strongly data-limited at the present time. This is known because (a) trial data inversions and network optimization studies have shown that adding a few vertical profiles over continental interiors could dramatically reduce flux uncertainty (Rayner *et al*, 1996; Gloor *et al*, 2000); and (b) flux uncertainty due to sparse data is of the same order as the differences arising from very different transport models in estimating sources and sinks[17]. There are many opportunities to add substantial data constraints to the mass-balance of atmospheric CO_2 over regional scales (see Atmospheric, p.23). To do this effectively, additional network optimization studies must be undertaken that seek to quantify the reduction in uncertainty for proposed sampling sites before they are deployed. Such studies should also address alternative sampling methods, particularly airborne sampling, continuous monitoring, and remotely sensed concentration measurements.

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[16] http://www.cmdl.noaa.gov/ccg/globalview/co2/default.html

[*ins*] The issue is adding sites for flask sampling, based on network optimization studies.

Improved measurements of atmospheric composition

Improved vertical profiling of trace gases through the boundary layer and above, with flasks or continuous analysers, has long been recognized as one way to improve the scale linkage between fixed surface sites and the transport parameterisations. This is a key strategy incorporated into major continental carbon budget initiatives such as CARBOEUROPE and the proposed CARBON-AMERICA plan. The rapid development of mesoscale transport models, an integral part of the continental studies, also has the potential to improve the linkage in the case of the background observations, but has not been routinely exploited. Mesoscale atmospheric transport modelling in conjunction with continuous, high-precision trace gas measurements has the potential to be particularly useful over continental regions.

[*ins*] The issue is continuation of vertical profile measurements begun as part of continental-scale carbon budget experiments.

Availability of transport and emissions data

Atmospheric tracer transport inversions require detailed information about winds, turbulence, and convective transport by clouds at high spatial and temporal resolution. These data are typically available from operational forecast centres, but frequent changes in forecast models and the high costs of obtaining these data have precluded consistent and accurate real-time analysis. Trace gas transport by unresolved vertical motions (e.g. in thunderstorms) is an important control on concentrations, yet these transports are generally not archived by forecast centres and are therefore unavailable for inverse modellers. As more concentration data become available at higher spatial and temporal resolution (see Atmospheric, p.23), these data will become much more important for analysis of sources and sinks at regional scales.

To provide a useful constraint on process-based models of surface CO_2 exchange from atmospheric data requires detailed knowledge of combustion sources. These are currently reported on a national annual basis, and have been distributed as population and seasonal cycles in the research literature. Regional mass-balance constraints will require more detailed emission estimates by location (city) and date. This data once available will be extremely valuable for campaign-style scaling experiments. In addition, the measurements generally have low spatial density, thus necessitating use of proxy data (see Atmospheric, p.23).

The continuity and consistency issues are:

1. **[*ins*]** Nations making available location- and time-specific fossil fuel emission data. Currently nations aggregate their data to the national and annual scale before reporting it.
2. **[*ins*]** Archival and distribution of subgrid-scale vertical mass fluxes from operational weather analysis centres to facilitate atmospheric inverse modelling of sources and sinks.

THE KNOWLEDGE CHALLENGE[18]

This section contains a list of issues that are considered important to improving the carbon cycle observations, beyond the initial observing system. They include observations, observing approaches, and methodologies for making or using the resulting measurements. Most of the issues are in the purview of various IGOS Partners, although this is not a condition for including the items.

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[17] http://transcom.colostate.edu

[18] **sat** = primarily a satellite observation issue (implementation, development, or research)
ins = primarily an *in situ* observation issue (implementation, development).
dev = primarily research and development issue

Terrestrial

LAND COVER AND LAND USE

1. **[*dev*]** Effective methods are needed to map the global distribution and temporal variability of wetland cover types (Sahagian and Melack, 1998), possibly in conjunction with soil moisture monitoring (see below). This information is necessary to estimate carbon fluxes for wetlands.
2. **[*dev*]** Global land use products should be developed through an integrated *in situ*/satellite approach that uses a harmonized classification system and provides historical and current land use with the highest feasible spatial detail.
3. **[*dev*]** Consensus on the following methodological aspects is necessary: a common hierarchical land cover classification scheme, a common terminology for land use and protocol for data collection, and an agreement on minimum mapping units for land cover and land use at various scales.
4. **[*dev*]** Examine the trade-offs between spatial resolution and information obtained from medium resolution (200 m to 1000 m) satellite optical data for global land cover, fires and biophysical parameter extraction.

BIOMASS

1. **[*dev*]** New soil carbon estimation techniques need to be developed, using primarily a combination of *in situ* and modelling strategies. Given the costs and other limitations of current methods, new techniques are the main potential means for increasing the amount of actual observations. Direct satellite-based methods would be very desirable but no viable approaches are known at the present. However, satellite-based biophysical parameter products (page 12) may be helpful in a modelling approach. In addition to the new estimation techniques, new surveys of soil carbon also need to be promoted, and should include observations of the factors that regulate its distribution and dynamics so that effective models may be developed. New pedotransfer functions need to be developed for soil data from Eastern Europe to deal with variations in soil data caused by differences in soil analytical techniques. The existing field measurements should be fully used to update the 1:5 million soil map of the world; this is now underway through the combined work of FAO, ISRIC, UNEP and IUSS.
2. **[*sat*]** Satellite-based methods offer great promise in quantifying above ground biomass and its changes at high spatial resolution. Lidar, bidirectional reflectance measurements, and radar interferometric techniques (Rosenqvist *et al.*, 1999) are the most promising sensing methods. The satellite technology needs to be developed, beyond the current or planned sensors (VCL/ESSP, single-frequency SARs, and experimental multiangle optical sensors such as MISR/Terra and (lidar) and EPIC/Triana).
3. **[*ins*] [*dev*]** Effective techniques need to be developed to utilise forest and agricultural inventory data in quantifying biomass and its changes. In particular, this includes scaling algorithms for above and below-ground biomass for all major ecosystems (i.e. beyond those of economic interest), and should be conducted in conjunction with improved satellite observations. Allometry based on the fractal properties of plants holds promise to develop the relationships rapidly and cost-effectively.

SEASONAL GROWTH CYCLE

1. **[*sat*]** The use of new satellite sensing techniques (multi-angle optical, lidar) needs to be further investigated in combination with current data types. Important questions include improving LAI estimation accuracy at high LAI values and obtaining information on the spatial distribution of sunlit and shaded leaves within the canopy. The planned POLDER/ADEOS-II and EPIC/Triana will contribute in this respect, but their spatial resolution is limited. There is no planned follow-on to MISR/Terra.
2. **[*sat*]** An observing strategy needs to be developed to detect frost-free season duration at high latitudes and in mountainous areas. An experimental algorithm based on SAR imaging has been demonstrated (Frolking *et al.* 1999). SeaWinds

scatterometer on Quickscat provides an opportunity to test the concept.

FIRES AND OTHER DISTURBANCES

1. **[*sat*]** Satellite-based observation methods need to be developed to estimate the spatially and temporally varying fire intensity and fire burning efficiency (Ahern *et al.* 2000). These parameters are essential but presently missing inputs to quantifying carbon emissions to the atmosphere. The potential of data from new sensors of the MODIS type needs to be examined as an initial step.
2. **[*sat*] [*dev*]** Robust methods are needed to detect and quantify partial disturbances in forests such as insect damage and selective harvesting.
3. **[*sat*]** New methods are required to map areas in dense forests burned by 'ground fires' (in which the tree canopy is not seriously damaged, thus not detectable with medium resolution optical sensors). Among the current or planned sensors, very high resolution (few metres) optical images or canopy penetrating (imaging) lidars may be helpful, in combination with fire behaviour models.

SOLAR RADIATION

1. **[*sat*]** Development of daily PAR products from geostationary and polar orbiting sensors is needed. The aim should be spatial resolution near ~10 km and direct estimation for the PAR spectral region (0.4 - 0.7 micrometres).

SURFACE-ATMOSPHERE FLUXES

1. **[*ins*] [*dev*]** More accurate CO_2 concentration measurements should be made at the flux towers, using better instrumentation and frequent automated calibration to standard gases. An operational goal of 0.2 ppmv accuracy is attainable and would allow these measurements to be integrated into the worldwide observational network of trace gas concentrations (page 12). These measurements are an important link to the larger-scale flux estimates using atmospheric inversion.
2. **[*ins*]** Flux tower methodologies among the regional networks need to be standardized in several areas: (i) ecological measurements including characterization of site variables, phenology, soil, and site history; (ii) effective use of high resolution remote sensing measurements to characterise the flux - contributing areas; (iii) algorithms for data treatment (atmospheric corrections, data quality checks and assurance, and gap filling); and (iv) hardware and data communication.
3. **[*dev*]** A significant effort is needed to integrate tower-based fluxes and ecological information with larger-scale observations and analyses. A key approach is through the use of local flux and ecological data to constrain parameters in process-based models which are then applied over larger scales using satellite-derived products.

METHANE-RELATED PRODUCTS

1. **[*sat*] [*dev*]** Satellite observation techniques and modelling tools should be developed to estimate methane fluxes from wetlands in all major biomes. This includes effective use of satellite-derived products, especially land cover, surface wetness, and seasonal growth cycle. Experience obtained with CH_4 estimates from MOPITT/Terra as well as HIRDLS/Aura, TES/Aura, and GCOM-A1/SOFIS will be very valuable for the future evolution of satellite-based techniques.
2. **[*sat*]** Development of sensors to detect the depth to water table is an important area to pursue. Water table divides the aerobic part of the profile (producing CO_2) from anaerobic (producing CH_4), thus greatly affecting the composition and global warming potential of the gases emitted by the wetland ecosystems.

SOIL MOISTURE

1. **[*sat*] [*dev*]** Intensified research and development should be carried out leading to a satellite-based capability to monitor soil moisture worldwide (i.e. soil water content within the root zone; the depth varies by vegetation type but may be nominally considered to correspond to the 0-1 m layer). The experimental MIRAS/SMOS mission is an important step in this direction. Current efforts of GEWEX/BAHC, the LDAS project[19], and other related initiatives should be supported. They

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[19] http://ldas.gsfc.nasa.gov/index.shtml

should be structured to take full advantage of the planned NPOESS products and of the satellite data preceding NPOESS, including AMSR-E/Aqua, AMSR/ADEOS-II and GCOM. Soil moisture availability exhibits a major control on CO_2 uptake by vegetation. In addition to soil moisture, surface wetness (water content at or within a few cm from the surface, including flooded or saturated condition) provides an important constraint on trace gas exchange with the atmosphere, in both herbaceous and forested wetlands. Flooded forests can be satisfactorily mapped using satellite SARs, especially L-band SAR on JERS-1 and ALOS.

CANOPY BIOCHEMISTRY

1. ***[sat]*** Experimental programmes should be supported to determine the operational feasibility of producing robust estimates of canopy biochemical properties. Leaf nitrogen content is of most interest because of its role in photosynthesis and the close coupling between carbon and nitrogen cycles; it is most important in nitrogen-limited ecosystems such as the boreal forest. Based on the research to date, high resolution imaging spectrometry measurements are the most appropriate satellite observing strategy, and they might take advantage of the correlation between chlorophyll concentration and nitrogen content. The planned EO-1/Hyperion mission should provide a valuable contribution in this respect, as a first-time demonstration of the feasibility. However, significant additional effort will be required in this area.

Atmospheric

ATMOSPHERIC COMPOSITION AND TRANSPORT

1. ***[dev]*** Problems of relating point observations at surface sites to the scale of atmospheric transport representations (potentially significant at the mostly-marine GAW sites) become critical over terrestrial regions of strongly heterogeneous exchanges under low wind-speeds. Modelling studies have shown that added atmospheric observations in such continental regimes hold great potential for more robust inverse flux estimation. Interpretation of spatial and temporal patterns in trace gas composition under these conditions will require new field and modelling studies. Field campaigns including sampling from tall towers, tethered balloons, and light aircraft should be conducted in conjunction with ground measurements of fluxes and ecosystem condition, and would be used to test upscaling methods based on remotely sensed imagery. Process models and spatial data would then be coupled to mesoscale transport models to test their predictions against the airborne samples.
2. ***[dev]*** Continuous *in situ* CO_2 analysis would be highly advantageous, particularly in continental areas and in conjunction with high-resolution transport modelling because the full range of atmospheric mixing conditions at a site is sampled. This permits proper averaging of data (aided by local area atmospheric transport models). The value of multi-species information from flask sampling is also significantly enhanced when the sampling is carried out in conjunction with a continuous analyser. The challenge is to achieve much wider deployment of robust remotely-operated continuous CO_2 analysers, with an acceptable trade-off between logistical independence and precision. Deployment can also be extended to moving platforms (ships, aircraft) if potential vibration sensitivity is overcome. An important performance breakthrough in conventional Non-Dispersive Infra Red CO_2 analysis, the most precise technique currently employed in global studies, has recently occurred (Da Costa and Steele, 1997). The remotely-controlled operational system has substantially lower sample size requirements, much higher long term stability, and significantly lower operating costs. However, engineering development is required to miniaturise, ruggedise and decrease costs through mass production techniques. An interim deployment of cheaper low precision continuous CO_2 analysers is worthy of consideration.
3. ***[ins]*** The accuracy and resolution of the spatial distribution of CO_2 sources and sinks computed through atmospheric inversions would increase substantially with better characterization of the transfer and mixing behaviour of the atmosphere. In particular, subgrid-scale vertical mass fluxes are routinely calculated by operational weather forecast models, but are not reported or archived, yet

these are crucial for analysing trace gas spatial structure at mesoscales.

TECHNOLOGY DEVELOPMENT FOR TERRESTRIAL ENVIRONMENT

Increased deployment of continuous analysers and flask sampling on platforms which permit characterization and/or minimize surface layer influences (tall towers, balloon sondes, piloted and pilotless aircraft) is a key part of current approaches to the problem of CO_2 sampling and integration in the heterogeneous terrestrial environments. Results from these studies will have a significant input to both top-down and bottom-up studies of the carbon cycle. Consequently, improved calibration against primary standards is a challenge for these as well as for background monitoring sites. Several options offer promise:

1. ***[sat]*** Remote infrared CO_2 monitoring *via* satellite is the subject of considerable current interest. Although integrated column CO_2 can be obtained with a relatively low precision (~1ppm), the potential for reducing regional flux uncertainties, particularly in continental regions now poorly determined by surface observations, appears quite high. Given the lead-time for developing the required sensor technology, this area should be pursued as soon as feasible. Among the planned sensors, AIRS Aqua and IASI MetOp will provide opportunities to develop and test this concept.
2. ***[dev]*** Another new technique of considerable promise is Fourier Transform InfraRed spectroscopy which provides relatively low precision but continuous, multi-species monitoring. In terrestrial systems, the potential for chemical identification and monitoring of significant sources is high.
3. ***[dev]*** Spatial and temporal coverage will be significantly expanded if a gap can be closed between instrument size and payload limits for the smaller, less expensive sampling options (drone aircraft, balloon sondes); technological developments in this direction should be encouraged.
4. ***[dev]*** There is a need to develop techniques for estimating CO_2 emissions from fossil fuels with a higher spatial and temporal resolution than presently feasible. Direct satellite sensing (see above) could make an important contribution in this respect.

ORGANIZATIONAL CHALLENGE

There are four major organizational challenges in establishing a global observing capability for terrestrial carbon:

- **Continuity and improvements of satellite and *in situ* observations.** For satellite observations, this can be addressed within IGOS-P as most of the satellite agencies are part of the decision process in CEOS. The situation is more complicated for *in situ* observations. For atmospheric *in situ* observations (e.g. trace gas concentrations) the link is through WMO to national agencies. For terrestrial ecosystems, the links between the national funding agencies and international programmes are weak. Internationally, GTOS and its sponsors (particularly FAO, UNEP, WMO) have national points of contact but at the national level, the programmes and funding are not typically handled centrally. It is therefore difficult and unwieldy to establish effective links between operational national terrestrial *in situ* observations and global carbon observation effort. *In situ* observation networks are gradually being linked (e.g. ecology, hydrology, permafrost) through initiatives such as GT-Net (Appendix 2.) but progress has been slow and will need to be accelerated if the *in situ* community is to contribute effectively to TCO.

- **Transition from research to ongoing operations.** This is an issue for most of the elements of the carbon observation theme, except for weather-related observations. A major reason is the relatively recent interest in the global carbon cycle and the associated experimental nature of the observing technologies and programmes. However, transition to routine operations is essential if IGOS-P is to achieve long-term, systematic observations that are required to meet the requirements (Chapter 2). This may best be achieved gradually, by pursuing the transition for individual components of the observation system as they mature. The initial candidates are satellite observations, atmospheric concentration measurements, and some *in situ* terrestrial observations.

- **Supporting research and technology development.** Improvements beyond the initial observing system will necessitate vigorous support for development in several areas, including: instrumentation for *in situ* and satellite observations (see Knowledge Challenge, p20); *in situ* networks enhancement and design optimization studies, in turn requiring the capability to evaluate trade-offs in performance based on various hypothetical improvements in the observations; and models and algorithms that are able to effectively use the improved observations and eventually perform well with reduced observations. Therefore, technology development needs to be carried out in close collaboration with the research community, internationally as well as nationally. This is already recognized by some current programmes (e.g. the EU Fifth Framework Programme).

- **Coordination.** From the above it is evident that the establishment of systematic observations of the terrestrial (and the linked atmospheric) component of the global carbon cycle is a complex undertaking, mainly because the complexity of the carbon cycle intersects with the political and economic structures that have been set up at the international as well as national levels. Effective and efficient arrangements for global carbon cycle observations must therefore rely on several components, most of which have multiple clients and are sponsored for different reasons. Since it is unlikely that this situation will change appreciably in the near future, it is essential that an effective coordination mechanism be established by IGOS-P. This mechanism needs to meet the needs of the three observing systems as well as those of international research programmes. A possible way forward is outlined in Chapter 6.

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Data Products, Services, Archives and Access

TABLE 1 SHOWS A LIST OF THE MAIN PRODUCTS THAT SHOULD BE THE FOCUS FOR GLOBAL TERRESTRIAL CARBON OBSERVATION INITIATIVE DURING THE INITIAL PERIOD. AS NOTED IN SECTION 3.2, MANY OF THESE OR SIMILAR PRODUCTS ARE NOW GENERATED OR BEING PLANNED OVER VARIOUS GEOGRAPHIC AREAS (APPENDIX 2). The raw data originate from different agencies (satellite and *in situ*, different countries), and the preparation of individual products may require access to one or more other data types or input products. Also, the data and products exist at various levels, from raw observations to synthesized high level products generated by incorporating lower level products into models.

The above considerations imply that to be effective, the IGOS carbon cycle theme must be based on a coordinated approach to data and information system issues. Importantly, this would also facilitate secondary and spin-off uses of the products, thus enhancing the impact of the IGOS initiative. Appropriate models exists, for example, GCOS products are generated through cooperation among primary data collectors, data quality monitoring centres, and product generation/analysis centres (refer to GUAN[20]). The IGOS Ad Hoc Working Group on Data and Information Systems and Services also considered the generic issues involved and developed principles that should be followed. These principles will need to be applied to the carbon observation theme as a whole as well as to the contributing operations of the individual participating agencies; a way forward is proposed in Chapter 6.

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[20] http://www.gos.udel.edu/gcos/guanflow.htm

Table 1. Products for the initial period (3-5 years)+

Category	Products (digital georeferenced)	Spatial extent	Temporal frequency
Land cover	Land cover types and change	• Global and • Continental (NA, Europe, Asia, Africa, SA initially)	Annual to seasonal and 5 year
Land cover	Continuous fields	Global	Annual
Biomass[4]	Biomass density	Regional and biome-specific	Annual
Seasonal growth cycle	Leaf area index	• Region- and site- specific (campaigns) • Global	Sub-seasonal
Seasonal growth cycle	Growing season duration	• Region- and site- specific (campaigns) • Global	Annual
Fires	Burned area	• Continental • Global	Annual
Fires[4]	Burned biomass	• Continental • Global	Annual
Solar radiation[5]	SW solar irradiance	Global	Daily
Surface atmospheric fluxes	CO_2 flux and associated tower measurements	Network of sites	Sub-daily
Atmospheric concentration of CO_2 and other gases	Trace gas concentration	Network of sites	Weekly (or less)
Ecosystem productivity[6]	NPP	• Region- and site- specific (campaigns) • Continental • Global	Annual
Ecosystem productivity[6]	NEP	• Region- and site- specific (campaigns) • Continental • Global	Annual

+ NOTES:

1. The table presents an overview of major products for terrestrial carbon estimation that are needed for the TCO initiative. Most of these employ satellite data. Other observations or products are also needed but not listed here They include meteorological products soil databases, and others (Cihlar, Denning and Gosz (2000); refer also to Chapter 4.).
2. Many of the above products are now produced by space agencies, research projects, or observation networks. Most of the products are being continually improved through product validation, supporting research and model development, and the reprocessing of archived data. The agencies and projects involved in these typically have specific plans for improving the products. Importantly, new programmes are now being developed in various countries that will make further progress in these areas
3. Where different geographic areas are shown (spatial extent), the quality and documentation of the products is higher at the site and regional levels. The improvements of global products hinges on progress being made through regional or campaign initiatives.
4. Current limitation is lack of consistent measurements over large areas, progress depends on improved satellite measurements.
5. Current products have coarse spatial and temporal resolution.
6. Experimental ecosystem productivity maps have been generated for specific areas and years, using the above products as input (see Ecosystem productivity, p.18) The NPP (annual gross carbon uptake) and NEP (annual source/sink distribution) products are presently model- dependent and are also limited by the quality of the existing input products. Plans are in place to generate global NPP products, using new satellite data.

All product generation, archiving and distribution centres should be accessible through Internet. The generally available low-speed Internet links should facilitate access to output products and to low-volumes of raw data/low level products. In addition, as many as possible centres should be connected with high performance, wide bandwidth links. High performance research and education networks (e.g. NASA NREN, Asia Pacific Advanced Network), now available in several countries, can be used to facilitate exchange of high volume data among the participants and the generation of products. Internet will facilitate product access to policy users, conventions, and others. In addition to existing agencies (Appendix 2), new contributors will also be able to join, such as: research agencies; operational agencies; World Data Centers for trace gases, meteorology, renewable resources and environment[21]; and educational institutions. Special attention will need to be given to *in situ* data, as their timely availability is critical for various derived products and the widely distributed points-of-entry present special challenges. The detailed arrangements for product generation, quality control, access and archiving will need to be worked out among the contributors based on the principles defined by IGOS-DISS. Cihlar, Denning and Gosz (2000) described several existing tools and mechanisms that could be used in this process.

An important advantage of using Internet is the ongoing growth of up-to-date communication and data exchange capabilities, as the technical performance of individual sites undergoes ongoing enhancements. This will also facilitate the transition from research to operational status as the observation networks and products mature, since the technology employed will remain similar. Another advantage is the ability to make the products widely known and accessible to a large audience worldwide, thus increasing the impact of the actions by IGOS-P and other contributors. However, for the Internet-based approach to function effectively, it will be necessary that data handling and archiving policies are harmonized, and that data and products are easily located in the holdings of the various participants. A single-point entry should be established that provides an overview and links to other sites. Suitable technical capabilities have already been developed by CEOS/WGISS[22], GOSIC[23], ORNL[24], and others. They will need to be employed in a coordinated manner by the agencies participating in the IGOS carbon cycle observation theme.

The required basic data products for the terrestrial domain have been defined elsewhere (Cihlar, Denning and Gosz, 2000; Chapter 4.). Agreements will have to be reached regarding data products, documentation, archiving contributions and responsibilities of the participating agencies, and access to data and products. Data documentation formats have been established by various initiatives (e.g. FDGC[25]; GCMD[26]) and are becoming widely used; these should be considered for adoption by the carbon observations. Short- and long-term archiving issues will need to be worked out among the participating agencies. IGOS-DISS recommendations (IGOS Ad Hoc Working Group on Data and Information Systems and Services, 2000) regarding access to data and products should be followed. Based on the experience of many groups, it is also essential that the data processing and archiving arrangements accommodate reprocessing of archived data, permitting generation of better products as the algorithms and models improve and thereby increasing the impact of the initial investments at a modest additional cost.

Assuring that the data and products have a defined and understandable quality assurance attached to them is highly important. Furthermore, for long-term continuity, the history of quality control needs to be well described. The objective should be to ensure that a potential user knows and can rely on the quality assurance assigned to a product or data set. For complex products this can be a difficult task but is essential. One means of achieving better quality control is to establish a standardised method for calibrating sensors used in the Observing System.

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[21] http://www.ngdc.noaa.gov/wdc/

[22] http://wgiss.ceos.org/index.htm

[23] http://www.gos.udel.edu/

[24] http://mercury.ornl.gov/

[25] http://www.fgdc.gov/

[26] http://gcmd.gsfc.nasa.gov/difguide/difman.html

The issue here is for data providers to describe adequately and in a uniform way the quality of their data and products, and to subscribe to a uniform standard of calibration procedures for sensors.

6

An initial observing system

NUMEROUS ACTIVITIES ARE PRESENTLY UNDERWAY OR PLANNED THAT ADDRESS TERRESTRIAL CARBON OBSERVATION IN VARIOUS GEOGRAPHIC REGIONS (SEE CHAPTER 3 AND APPENDIX 2). IN GENERAL, THESE ACTIVITIES CONCERN SPECIFIC OBSERVATION OR RESEARCH ASPECTS AND ARE NOT WELL COORDINATED. THEY ARE ALSO NOT DESIGNED IN A SYSTEMATIC FASHION TO PROVIDE CONSISTENT INFORMATION AT THE GLOBAL SCALE. Thus, while these activities are potentially important building blocks for systematic global carbon observation, there is a need for a focused effort and a common vision to be pursued. The following goals are outlined for the initial terrestrial carbon observing system, with a timetable conditioned by the Kyoto Protocol schedule:

1. By 2005, demonstrate the capability to estimate annual net land-atmosphere fluxes at a sub-continental scale (10^7 km^2) with an accuracy of +/- 30% globally, and at a regional scale (10^6 km^2) over areas selected for specific campaigns with a similar or better accuracy;
2. By 2008, improve the performance to better spatial resolution (10^6 km^2) globally and an accuracy of +/- 20%;
3. In each case, produce flux emission estimate maps with the highest spatial resolution enabled by the available satellite-derived and other input products.

Based on the requirements discussion (Chapter 4 and 5), the resulting carbon observing system should be:

- global and long-term in scope, nationally sponsored, and internationally coordinated;
- multi-user, needs-driven; and focused, but accommodating to complementary uses (e.g. global hydrological cycle);
- based on quality controlled observations and data products, and on full and open exchange of data and information;
- adaptable to changing needs and capabilities; and evolving with improving observation instruments, platforms, techniques, and uses (see below);
- helping to build capacity on a global basis.

Although the Kyoto Protocol is an important factor in the establishment of global terrestrial carbon observation, the complete range of requirements is considerably more diverse, thus the observing system must respond to the broader set of requirements. The specific reporting requirements for the Kyoto Protocol are under discussion and the result will have implications for the terrestrial carbon observing system. A previous workshop conducted an initial assessment of the potential contributions of satellite observations to various areas of the Kyoto Protocol (Rosenqvist *et al.*, 1999).

The following sections outline an approach to the implementation of the initial observing system.

COMPONENTS

A successful implementation of a comprehensive terrestrial carbon observing system that assimilates various inputs (see page 6) must necessarily be an evolving process. The most essential elements are listed below, and the main relevant currently existing activities that should be part of the initial observing system are also identified:

- Atmospheric sampling for multiple trace gases from *in situ* and airborne platforms: the GLOBALVIEW-CO_2 project and its proposed GLOBALHUBS measurements enhancement (see Long-term continuity, p.19); regional carbon programmes (CARBOEUROPE; Australian Carbon Project; US carbon cycle programme).
- Collection of spatial data and imagery needed to apply process models: satellite programmes (see pages 12-20 and Appendix 3).
- Estimation of local to global daily carbon fluxes from gridded spatial data using models and scaling algorithms:
  - Global: the GOFC project, in collaboration with: GTOS NPP project; the World Fire Web project; FAO and UNEP; IGBP projects (GCTE, GAIM, BAHC, IGAC, LUCC);
  - Regional: regional terrestrial carbon programmes, including: CARBOEUROPE; Australian Carbon Project; LBA; US carbon programme; carbon programmes in Canada, Japan, Russia.
- Estimation of global to regional sources and sinks by atmospheric inverse modelling:
  - Global: IGBP (TransCom);
  - Regional and national: CARBOEUROPE, LBA/Brazil, the US Carbon Cycle Programme, Australian Carbon Project.
- *In situ* measurements of ecosystem carbon fluxes and pools to provide continuous long term data of carbon and energy exchanges in a range of biomes and quantify inter-annual variability of ecosystem responses to climate, to validate the derived products, and to improve the understanding and models of the processes of carbon exchange: FLUXNET; ILTER; GT-Net; FAO (to access national inventories); regional networks; IGBP networks (SOMNET, FACE).
- Atmospheric observing campaigns to allow direct estimation of area-mean carbon fluxes and flux uncertainties over field sites for an evaluation of models and scaling algorithms: regional carbon programmes (see above).
- Data analysis, product generation and archiving centres. In the short term, these centres will be located with agencies providing the data and products, representatives of whom are listed above. Their participation will need to be dis-

cussed with the individual agencies. A subsequent transition to an ongoing system should be based on lessons learned in the initial period.
- An effective data and information handling system (Chapter 5), including some form of reporting and feedback between the individuals and organizations that generate products and services, the users of these products, and the sponsors of the carbon observing system.
- An international coordinating office.

IMPLEMENTATION

To begin the implementation process, an implementation team (IT) should be set up that is linked to the IGCO framework and to existing projects and activities related to TCO. It is proposed that the TCO IT should be a subgroup of the (yet to be defined) IGCO implementation structure, and to place it within the Global Observation of Forest Cover (GOFC) project as the fourth theme (in addition to the existing land cover, fire, and biophysical functioning themes). In 2000, GOFC became a GTOS panel and works closely within that framework by developing networks and capacity to participate in global change studies. The rationale for link within IGCO is obvious. The placing of the TCO IT within GOFC has several advantages: building on the progress of GOFC to date (product definition and development, support of agencies, regional activities and linkages), enhancing GOFC by bringing in the 'top down' component, and ensuring coherent development of the IGOS-P terrestrial carbon observation in the future. With the encouragement of GTOS, the GOFC Scientific and Technical Board (GOFC STB, 2000) has already considered broadening its remit to cover all terrestrial ecosystems; formalizing this expanded scope would be required if TCO were be be undertaken as a theme. Within GOFC, the TCO implementation team would thus have a status that would allow it interact freely with IGCO on technical matters and report directly to GTOS and IGOS-P on programme and policy matters. The TCO terms of reference would be drafted by the lead partner in consultation with other partners, including IGBP, GCOS and others.

To make progress in the implementation of systematic observations of the carbon cycle, the TCO IT should take action at several fronts.
- Satellite data and products: the continuity and data product generation issues need to be addressed through discussions and commitments by CEOS members, using SIT as appropriate.
- Atmospheric *in situ* concentration measurements: the IT needs to involve the existing network (GLOBALVIEW-CO$_2$), WMO and national contacts to ensure continuity and to assist in improving these data sets.
- Terrestrial *in situ* measurements: These are considered separately for (i) flux measurements and (ii) other ecosystem observations.
  - Flux measurements. In the long term, ecosystem flux measurements should become part of operational *in situ* observing networks (see page 17 and page 21). However, reaching this stage will require further work, primarily technology development to reduce the initial and ongoing costs of operation. Thus, the immediate priority is to ensure continuing operation of the current FLUXNET, presently funded from research budgets. The present IGOS Partners provide the best links to national funding agencies (e.g. CEOS, GCOS through the SBSTA-mandated reporting on national networks, etc.). The improvements in flux networks could thus be pursued by IGOS-P members through concerted (e.g. GTOS IGBP GCOS) and individual (within countries) actions. The TCO IT should work through these mechanisms to ensure continuity and further expansion of the flux networks.
  - Ecosystem observations. The harmonization of existing national or regional ecological observing networks and inventories is a complex task. There is a need for in-depth examination of the issues involved in compiling global (or regional) data sets of *in situ* observations, by bringing together representatives of networks (global, regional, national) that have been acquiring data needed by TCO. Current efforts (e.g. the North America Eurasia carbon balance project) should shed light on the best ways to proceed in this area. Further developments in mandated

reporting procedures for the Kyoto Protocol will also be important to help clarify the possible mechanisms and most promising avenues for the future.

An agreement on the overall framework for data and products is very important because the ultimate implementation will take place primarily through national agencies (within countries or as a contribution to the international effort). The coordinating roles of international representatives of the national agencies are therefore paramount. Consequently, the TCO IT should involve at least the following IGOS partners:

- CEOS, representing space agencies;
- WMO, representing atmospheric agencies and associated projects, particularly GLOBALVIEW-CO_2;
- GTOS and FAO, representing agencies with terrestrial observation interests (regional networks, others);
- IGBP and ICSU, representing science agencies.

The TCO IT should also ascertain the need to establish a 'base year', as an initial stimulus to coordination of data preparation and product generation efforts. Among the candidates are 1990 (reference year for the Kyoto Protocol) and ~2000 (Millennium Ecosystem Assessment[27]).

AWARENESS AND VISIBILITY

The effectiveness of an evolving carbon observing system will depend on the mechanisms established to communicate with the sponsors and clients of the system. These will ensure that the system addresses important issues and makes the contributions needed. Given that the implementation will necessarily be 'distributed', the communication challenge will be very large. The mechanisms employed should not only be sensitive to the changing requirements, but should also provide up-to-date information on existing observation capabilities and products, as well as the performance of the observing system as a whole (IGOS Ad Hoc Working Group on Data and Information Systems and Services, 2000).

In addition to the direct community of product users, it is important to ensure communication with other potential users and the general public. There is also a continuing need to inform the relevant bodies at a national and international level of the importance of a sustained and systematic approach to carbon cycle observations. Equally important is for the general public to be made aware of the benefits of understanding the processes that influence the carbon cycle, and of the need for the global observations. All partners within IGOS have a role in this area, to develop an overall plan, and then keep each other informed of the activities undertaken.

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[27] http://www.ma-secretariat.org/

7

Conclusion and recommendations

IT IS CONCLUDED THAT:

1. There are several compelling reasons to begin establishing a global carbon cycle observing system:
   - the commitment by governments to environmental conventions and multilateral agreements that specify or imply the need for terrestrial carbon information, including the UN Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity, and the Convention to Combat Desertification;
   - the acceptance by Agenda 21 and the Conference of Parties of the requirement for systematic observations as part of the UNFCCC, and the related establishment of global observing systems for climate (GCOS) and terrestrial environments (GTOS);
   - the well-known need for information on the productivity and changes of terrestrial biosphere to permit sustainable development and resource management;
   - the well-established need for improved knowledge of the carbon cycle, its variability, and its likely future evolution, dictated by the desire to develop the most effective national and global policies to deal with climate variability, change, impact and adaptation.
   - Although the Kyoto Protocol is an important factor in the establishment of terrestrial carbon observations, the complete range of requirements is considerably more diverse, thus the terrestrial carbon observing system must respond to the broader set of requirements.

2. Based on previous detailed studies of requirements and the synthesis carried out as part of the IGOS planning, an initial observing system for terrestrial carbon can be established by employing present capabilities and activities. The main components are satellite observations, *in situ* atmospheric and ecosystem observation networks, digital data bases of key terrestrial ecosystem properties, integrative models, and associated research and development activities that will contribute to ongoing improvements in the performance of the observing system. Both new and previous data are important to the observing system.
3. Way forward involves participation of a number of existing satellite programmes, observation networks, and pilot and research projects. These may be accessed through coordinating international programmes and organizations, especially CEOS, FAO/GTOS, WMO, and IGBP. Because of the economic and social importance of many aspects of the carbon cycle, numerous terrestrial/atmospheric observation initiatives have been undertaken or are planned.
4. The primary roles for IGOS-P are to ensure that gaps in the observing systems are filled; that continuity, consistency and ongoing improvements in the comprehensiveness and quality of the observing capabilities are achieved; and that effective coordination and collaboration at the global level are facilitated. These are necessary in view of the diverse satellite and *in situ* data contributions required from national and international organizations.

It is recommended that IGOS Partners:

1. Approve this report and request the IGCO theme team to use it in preparing the IGCO theme report.
2. Request SIT to review and comment upon the commitments to existing and planned missions and programmes (Appendix 3.).
3. Examine the specific continuity and knowledge challenge issues identified in this report and where feasible, accept responsibility for addressing the gaps.
4. Take the following initial steps toward TCO implementation, within the IGCO framework:
   a) Identify lead IGOS Partner(s) responsible for TCO implementation;
   b) Charge the lead partner to prepare draft terms of reference in consultation with the Partners and to establish a TCO Implementation Team as outlined in Chapter 6, p.32;
   c) Request TCO IT to submit a draft work plan with required IGOS-P contributions (beyond those in recommendations 2). and 3). above) within 4 months of its establishment;
   d) Agree to support the work of TCO IT by making available staff and financial resources for its activities.

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Appendix

Examples of terrestrial carbon information users

Programme	Sponsor	Data used/needed	Coverage (spatial, time frame)	More information
Global/ International				
IPCC	UN FCCC	Ecosystem productivity	Global; past, present	http://www.ipcc.ch/
IGBP (several core projects)	Countries or regions	All variables (pages 12–24)	Global; past, present	http://www.igbp.kva.se/progelem.html
Forest resources assessment	FAO	Land cover and changes, biomass, fires, productivity	Global; every ~5 years	
Global Environmental Outlook	UNEP	All variables (pages 12–20)	Global; present; every 2 years	http://www1 unep.org/unep/eia/geo/reports.htm
NGOs (WRI, WCMC, others)	Various public and private	Land cover and fires, changes, biomass, productivity	Global, regional; present	http://www.wri.org/ http://www.wcmc org.uk/
Convention on Biological Diversity	Countries	Land cover and changes, biomass, fires, productivity	National to global; past, present	http://www.biodiv.org/chm/index.html
Convention to Combat Desertification	Countries	All variables (pages 12–20)	National; present	http://www.unccd.de/
National				
Carbon accounting	Countries, e.g.: Australia US Norway	All variables (pages 12–24)	Present; national; project - based	http://www.greenhousegov.au/ncas/ http://www.eia.doe.gov/oiaf/1605/ggrpt/ http://odin.dep.no/md/publ/climate/
Resource planning (vegetation, forest)	Countries, e.g.: Australia Africa Canada	All variables (pages 12–24)	Present; national or sub-national	http://www.nlwra.gov.au/ http://metart.fao.org/default.htm http://nfis.cfs.nrcan.gc.ca/
Resource management: fire – related	Countries, e.g. Africa, Indonesia, various others	Fires; land cover and change; biomass	Present; national	http://www.fs.fed.us/global/globe/africa/ http://www.iffm.or.id/ http://www.ruf.uni-freiburg.de/fireglobe/
Resource management: crops, water	Countries (Africa,..)	Land cover and change, biomass, productivity	Present; national	http://www.fao.org/WAICENT/FAOINFO/AGRICULT/agl/aglw/

APPENDIX 2

Examples of existing providers of carbon cycle-related observations

Type (*in situ*, satellite; main ones only)	Sponsor*	Data/products provided	Coverage (spatial; temporal)	More information
1a. *In situ* terrestrial				
FLUXNET	Countries/ IGBP/WCRP	Ecosystem data and fluxes; micromet. data	All continents (except Antarctica)	http://www-eosdis.ornl.gov/FLUXNET/
ILTER	Countries/ ICSU	Ecosystem data	21 countries	http://www.ilternet.edu/
GT-Net	Countries/ GTOS	Ecosystem data	84 countries, ~1300 sites	http://www.fao.org/gtos/PAGES/Gtnet.htm
FAO	Countries	Soil data	Global	http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGL/agll/prtsoil.htm
SOMNET	Countries/ IGBP	Soil data	~70 sites, 6 continents	http://www.iacr.bbsrc.ac.uk/res/depts/soils/somnet/tintro.html
World Data Centre for Soils	Countries+/ ICSU (+The Netherlands)	Soil data	All continents	http://www.isric.nl
1b. *In situ* atmospheric				
GLOBALVIEW-CO_2	Countries/ WMO	Trace gas concentrations	Global; ~weekly	http://www.cmdl.noaa.gov/ccg/globalview/co2/default.html
2. Satellite				
Fine resolution	NASA/CEOS	Images, land cover	Global	http://eosdatainfo.gsfc.nasa.gov/
	CNES/CEOS	Images, land cover	Global	http://www.spot.com/
	NASDA/CEOS	Images	Global	http://www.eorc.nasda.go.jp http://www.eoc.nasda.go.jp
	CSA/CEOS	Images	Global	http://www.rsi.ca/storefront/store.htm
Medium to coarse resolution	NASA/CEOS	Images, land cover and change; LAI; fires; CH_4, solar radiation; NPP	Global	http://ivanova.gsfc.nasa.gov/daac/ http://www.gewex.com/srb.html
	NOAA/CEOS	Solar radiation, images	Global	http://psbsgi1.nesdis.noaa.gov:8080/PSB/EPS/EPS.html
	NASDA/CNES/ CEOS	OCTS, POLDER	Global	http://www.eorc.nasda.go.jp http://www.eoc.nasda.go.jp
	ESA/JRC (WFW)/ EC	Fires	Global	http://www.gvm.sai.jrc.it/
	CNES/SNSB/ OSTC/SAI/EC	Images; land cover and change; fires; ecosystem productivity	Global	http://www.vgt.vito.be/ http://vegetation.cnes.fr

* Both the direct sponsor (usually a national agency) and the international umbrella organisation are listed

[illegible]

Status of satellite missions relevant to terrestrial carbon cycle observations*

AGENCY	MISSION	Carbon cycle sensors	CATEGORY**
CAST	***		
CNES	SPOT-3,- 4	HRV	1
CNES, EU	SPOT-4, SPOT –5	HRG, VEGETATION	
CSA	Radarsat -1, -2	SAR	1
ESA	ENVISAT-1	ASAR, MERIS, AATSR, SCIAMACHY	1
ESA	ERS-2	ATSR, AMI	1
ESA, CNES	SMOS ***	MIRAS	1
EUMETSAT	METOP –1, -2, - 3	AVHRR/3, IASI, ASCAT	1
EUMETSAT	MSG	SEVIRI	1
INPE	MECB SSR-1, -2	OBA	Planned
ISRO	IRS -1C, -1D	LISS-III, PAN, WIFS	
ISRO	IRS- P2, -P5, -P6	LISS-II (-IV), WiFS, HR-PAN, AWiFS	
ISRO	IRS- P3, -P4	MOS, WiFS, MSMR	
NASA, NASDA	EOS Aqua	CERES, MODIS, AIRS, AMSR-E	1
NASA	EOS Aura	HIRLDS, TES	
NASA, METI	EOS Terra	ASTER, CERES, MISR, MODIS, MOPITT	1
NASA	ESSP/VCL	MBLA	
NASA	ICESat	GLAS	1
NASA	QuikScat	SeaWinds	1
NASA (data buy from OSC)	OrbView-2 (SeaStar) ***	SeaWIFS	1
NASA	TRIANA***	EPIC	
NASA	NMP/EO-1	ALI, Hyperion	4
NASA, USGS	Landsat	ETM+	1
NASA, NASDA	TRMM	CERES, VIRS, PR, TMI	
NASDA, METI	ALOS	AVNIR-2, PALSAR, PRISM	1
NASDA, NASA	GCOM – B1, - B2 ***	SGLI, AMSR F/O, AlphaSCAT	2
NASDA, CNES, NASA,JME	ADEOS-II	GLI, POLDER, AMSR, ILAS-II, SeaWinds	1
NASDA, ESA, JME	GCOM – A1, - A2 ***	ODUS, SOFIS, SWIFT	2
NOAA,NASA,DOD	NPOESS***	VIIRS, ASCAT, CMIS	3
NOAA	TIROS	AVHRR	
NOAA	GOES 8-11	Imager	1
NOAA	GOES - N,O,P,Q	Imager, SEI	1

* Note: the table includes only missions directly linked to carbon observations and products; other missions may provide supplementary information (e.g. meteorological missions, or those listed in the Ocean Theme)

** Category: 1 = confirmation and timing of missions already planned ; 2 = proposed missions using known technology ; 3 = transitioning of research instruments/missions into operational ; 4 = development of new technologies, products or missions

*** Not in the WMO/CEOS database

APPENDIX 1

Theme team members

Name	Agency	Programme represented
Ahern, Frank	CCRS, Canada	GOFC, CEOS
Arino, Olivier	ESA ESRIN, Italy	IGBP, CEOS
Belward, Alan	JRC, Italy	GOFC, IGBP
Bretherton, Francis	U. Wisconsin, US	GOSSP
Cihlar, Josef	CCRS, Canada	GTOS, GCOS, CEOS
Cramer, Wolfgang	PIK, Germany	IGBP
Dedieu, Gerard	CESBIO, France	CARBOEUROPE, CEOS
Denning, Scott	Colorado State U., US	IGBP, USGCRP
Field, Christopher	Stanford U., US	IGBP, USGCRP
Francey, Roger	CSIRO, Australia	IGBP, WCRP
Gommes, Rene	FAO, Italy	Conventions, FRA, GTOS
Gosz, James	U. New Mexico, US	GTOS, ILTER
Hibbard, Kathy	U. New Hampshire, US	IGBP
Igarashi, Tamotsu	NASDA, Japan	CEOS
Kabat, Pavel	Wageningen U., The Netherlands	GEWEX, BAHC, LBA, CARBOEUROPE
Olson, Richard	ORNL, US	USGCRP, IGBP, FLUXNET
Plummer, Stephen	NERC, UK	CEOS
Rasool, Ichtiaque	CNES, France	ISLSCP
Raupach, Michael	CSIRO, Australia	IGBP, Ozflux
Scholes, Robert	CSIR, South Africa	IGBP, GTOS, GCOS
Townshend, John	U. Maryland	GOFC, SIT/IGOS, CEOS
Valentini, Riccardo	U. Tuscia, Italy	IGBP, FLUXNET, CARBOEUROPE
Wickland, Diane	NASA, US	USGCRP, CEOS

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5. Terrestrial Carbon Observation: The Frascati report on *in situ* carbon data and information (E) **

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P	Portuguese		
S	Spanish		

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The Integrated Global Observing Strategy Partnership (IGOS-P) is using specific policy-relevant themes as an approach to implementing systematic global observations. In November 1999, IGOS-P requested the Global Terrestrial Observing System, with FAO support, to lead the Terrestrial Carbon Cycle theme. In response to the request, the Terrestrial Carbon Theme Team was established to prepare this report. The report identifies a set of systematic, long-term terrestrial and atmospheric observations needed to implement an effective terrestrial carbon observation programme, highlights a number of challenges that need to be addressed, and outlines an approach to implementing an initial observing system. "Terrestrial carbon" refers to carbon contained in terrestrial vegetation or soil stocks and the fluxes from or to the atmosphere through which it participates in the global carbon cycle.

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